NAVAL RESEARCH PROGRAM

NAVAL POSTGRADUATE SCHOOL

2020 ANNUAL REPORT

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Fiscal Year 2020
Annual Report

NAVAL RESEARCH PROGRAM

NAVAL POSTGRADUATE SCHOOL

June 2020

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Naval Postgraduate School (NPS) Naval Research Program (NRP)
Research & Sponsored Programs Office (RSPO)
699 Dyer Road, Bldg 234 Monterey, CA 93943
NPS_NRP_POC@nps.edu
https://nps.edu/nrp

Provided by:
NPS President: Dr. Ann E. Rondeau, VADM USN Ret.
NPS Provost: Dr. Scott Gartner
NPS Dean of Research: Dr. Jeffrey Paduan
NPS NRP Program Manager: Mr. Matthew Kline
NPS NRP Deputy Program Manager: LtCol David Forbell
NPS NRP Integration Lead: Ms. Lois Hazard
NPS NRP IT & Student Component Manager: Ms. Sadie L. Hastings

MESSAGE FROM THE DEAN OF RESEARCH

I am pleased to support the Naval Postgraduate School (NPS) Naval Research Program (NRP) in the sixth complete fiscal year of the program. The studies sponsored within FY20 have made significant contributions to the Department of the Navy by providing insights to key operational problems that decision-makers face along with recommendations to support cost savings in a fiscally constrained environment. The NRP's program goals and execution support the Chief of Naval Operations vision of NPS as the Navy's applied research university. The interactions, experiences and knowledge gains that occur here are unique; it would be difficult to replicate them anywhere else in the world, which makes NPS an invaluable Fleet asset.

This report highlights results from the spectrum of NPS NRP research activities conducted on behalf of both Navy and Marine Corps Topic Sponsors during the 2020 fiscal year. Executive summaries from the research projects are included in the report. While most of those summaries detail final results, some projects have multi-year project lengths. In those cases, progress-to-date is reported.

NRP is one critical component of the overall NPS research portfolio. Under the stewardship of the NPS president, it utilizes a dedicated block of research funding to assist the operational naval community with timely studies while also informing NPS students and faculty about the latest operational priorities. As such, NRP projects are excellent complements to the other faculty-driven research projects, which tend toward the basic research program areas.

As we review results from 2020, we acknowledge that the work completed this year was constrained due to the global pandemic. While travel to collect data and meet with project stakeholders occurred differently this year, our faculty and students persevered to execute the work and build plans for future projects.

Finally, the many benefits that accrue through the NPS NRP depend on the wholehearted participation of the NPS faculty, the NPS students, and the many Topic Sponsors from across the Navy and Marine Corps headquarters commands. My thanks to all who have participated during this program year.

Sincerely,

Dr. Jeffrey Paduan NPS Dean of Research

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Naval Research Program Overview

The Naval Postgraduate School (NPS) Naval Research Program (NRP) is funded by the Chief of Naval Operations and supports research projects for the Navy and Marine Corps. The NPS NRP serves as a launch-point for new initiatives which posture naval forces to meet current and future operational warfighter challenges. NRP research projects are led by individual research teams that conduct research and through which NPS expertise is developed and maintained. The primary mechanism for obtaining NPS NRP support is through participation at NPS Naval Research Working Group (NRWG) meetings that bring together fleet topic sponsors, NPS faculty members, and students to discuss potential research topics and initiatives.

Background

The NRP was established in 2013 to leverage the expertise and experience of NPS' multidisciplinary faculty and naval (Navy and Marine Corps) student body to complete relevant, cost-effective research that addresses operational issues for the naval community*. Naval research, analyses topics, and focus areas are sponsored by numerous agencies within the Department of the Navy (DoN). The NPS NRP has developed as a standardized, systematic vehicle to leverage NPS multidisciplinary faculty and student research capabilities in response to demand signals across the DoN. It serves to execute research that adds value to the DoN through research efforts (Research Development Test and Evaluation (RDT&E) funding) at NPS. The NPS NRP in no way replaces the traditional, independent, external research development processes used by NPS faculty (e.g., Broad Area Announcements, Requests for Proposals), but rather is intended to complement those efforts. *Other federal agency sponsors may choose to participate in the NPS NRP working groups with their own funding.

Organization

The organization of the NPS NRP is based upon an annual research topic solicitation process that merges Department of Navy research, analysis, and studies requirements with NPS faculty and students who have unique expertise and experience. This process creates opportunities for NPS faculty and students to actively contribute to timely, real-world research, study, and analysis issues. The continual process begins with topic submission from the naval enterprise. Topic sponsors and NPS faculty collaborate at the annual convening of the NRWG on site at NPS each spring.

The NPS NRP also draws ideas from a Topics Review Board (TRB) comprised of Navy and Marine Corps senior military and/or civilian representatives from each of the responding operational command/activities, headquarters, or systems commands as well as a senior leader from NPS. TRB recommendations are forwarded to the NPS president for concurrence and coordination with the Vice Chief of Naval Operations and Assistant Commandant of the Marine Corps. The review board conducts thorough reviews of proposed topics and research, to ensure funding is available to support topics with the highest priority within the DoN.

Mission and Goals

The NPS NRP mission is to: provide operationally relevant research experiences to NPS faculty members, provide operationally relevant thesis opportunities to NPS students, and provide useful results from research projects and studies to Topic Sponsors across the naval enterprise. The goals of the NPS NRP are to:

- Become a recognized partner from which naval organizations seek out NPS in response to emerging requirements.
- Develop a ready pool of faculty research expertise to address these requirements.
- Offer a venue for NPS students to identify thesis research opportunities in areas directly relevant to naval challenges and research needs.
- Become the recognized leader for providing cutting-edge graduate education for naval officers that includes research complementary to the Navy and Marine Corps R&D requirements.

The NRP supports the awareness that "an active academic research program is vital to the quality of education provided to students, the attraction and retention of exceptional faculty members, and the provision of real-time, directly relevant deliverables to government sponsors (SECNAVINST 1524.2c dtd 21 Oct 2014)," and is postured to fulfill this DoN requirement. The NPS NRP convenes the annual NRWG as a forum for communicating, reviewing, validating, prioritizing and recommending research-topic challenges for consideration. Other topic solicitation methods may be employed in coordination with the NRWG to maximize the breath and scope of research topics. The process includes: opportunity for faculty dialogue with Topic Sponsors; faculty proposed responses to proposed topics that match academic interests and capabilities; and review, validation, and prioritization of matched topics against the most pressing joint requirements.

Program Administration

The NPS NRP is directed through NPS' Research and Sponsored Programs Office (RSPO). The Dean of Research (DOR) at NPS is designated as the lead agent and is responsible for NRWG execution, routing of post-TRB research requirements to NPS faculty and sponsors, and program management of the NPS NRP. The NPS NRP Program Office includes a program manager, deputy program manager, and small staff who are delegated the responsibility for day-to-day program management of the NRWG, as well as program and individual research project oversight on behalf of the DOR. The NPS NRP Program Office coordinates and liaises with NPS NRP designated points of contact/program area manager (PAM) counterparts from the various research sponsors.

Accomplishments

The NPS NRP represents a strategic statement about the tangible and intangible value that NPS provides the entire naval community. It has proven to be a significant integration vehicle for partnering naval sponsors and NPS researchers to deliver cost-efficient results. The NRWG is one manifestation of this integration process. More than 230 Navy and Marine Corps organizations throughout the naval community have actively supported opportunities to engage NPS faculty and students through participation in the NRWG event. To date, the NRP has collected over 2,500 potential and current research topics through NRWG events, while funding over 640 research projects. Embedding the NRP into the fabric of the NPS strategic planning process enables the school to rapidly respond to current and future “compass swings” in naval research requirements.

As a result of the NRP’s operations, NPS research is more directly aligned with the naval community than in prior years:

- In FY20, $10.8M, in funding distributed, which translated into 89 (85 represented in this report) distinct U.S. Navy and Marine Corps projects that cover the entire Office of the Chief of Naval Operations (OPNAV) staff, Fleet Forces (FF), Assistant Secretary of the Navy for Research, Development and Acquisition (ASN (RDA)), Strategic Systems Programs (SSP), and Marine Corps functional organizations.
- The NRP has mobilized the NPS faculty to focus more of their research on naval issues. Annually more than 250 civilian/military faculty from all four academic schools join the NRP effort, highlighting NPS’ campus-wide commitment to naval research.
- Cross-campus, inter-departmental research partnerships represent nearly half of the projects. They provide an advantage from the application of integrated perspectives and resulting multidisciplinary approaches.
- The NRP enjoys robust student engagement, leveraging the students’ previous operational experience and newfound knowledge from graduate studies. There were over 188 United States and foreign thesis students collaborating with faculty on 54 of the 85 projects.

*Executive summaries for three FY19 projects are included in this annual report but are not reflected in the FY20 Annual Report statistics.

ASN(RDA) - Research, Development, and Acquisition

NPS-20-N017-A: Assessing the use of Plasma Discharges to Remove Coatings as a Strategy to Develop an Improved Ability to Maintain and Repair Naval Structures

Researchers: Dr. Claudia Luhrs and Mr. Troy Ansell
Student Participation: ENS Nicholas Nathan USN and ENS Eric Reddick USN

Project Summary
Naval assets, including surface and undersea warfare vessels, undergo repair and maintenance operations that involve the removal of protective coatings. Mechanical and chemical means are currently employed for coating removal; however, there is a growing need for a more effective method. This study aimed to evaluate the effects of using plasmas to remove coatings during repair operations on the underlying metal. The work was performed as a collaboration between Naval Postgraduate School and Pearl Harbor Naval Shipyard and Intermediate Maintenance Facility. The focus of the work was to determine the changes in metal profile (topography), chemical composition of surface layers, and mechanical properties of plasma treated high yield steel specimens. Steel samples machined in two different orientations were coated with eight common coating systems, and subjected to plasma treatments using two different systems, both operating at atmospheric conditions. The properties and microstructures of pre- and post-plasma treated specimens were evaluated using tensile and hardness tests along microstructural analysis. Overall, it was found that the plasma treatment had only a minor effect on the properties of the underlying metal; strength and hardness for all specimens studied remained within the military standard recommended values while being an effective alternative to remove all the coatings studied.

Keywords: *naval alloys, repair strategies, plasma treatments, material characterization*

Background
Recent guidance from Navy's leadership calls for capabilities ashore and at sea, which will allow the fleet to operate globally, at a pace that can be sustained over time. One of the strategies suggested is to assess and develop options for improved ability and resilience to refuel, rearm, resupply, and repair.
The study conducted aligned very well with the later strategy since it focused on evaluating the use of atmospheric plasma systems to remove coatings on high-yield material used in a variety of Navy vessel applications as a strategy to accelerate repair operations.

The objective of the study was to evaluate the effect that using an atmospheric plasma system to remove coatings from the surface of alloys used in naval structures has in the substrate materials characteristics. Deeper understanding of the effects that plasma treatments have in the materials will help the Navy anticipate technological surprise and reduce the risk of transitioning to plasma strategies. Any advances in the field will improve our ability to maintain and repair naval structures.

Findings and Conclusions
The properties and microstructures of pre- and post-plasma treated specimens were evaluated using

tensile tests, hardness tests and microstructural analyses: Initial machining of the tensile test specimens was done using computer numerical control methods with careful control of temperature. Testing base plate in two different orientations helped established a baseline of properties, which were found to be within MIL-specification requirements. Tensile strength was well within required specification 690 MPa and the hardness only a bit above the expected 250 Vickers' hardness. The energy dispersive spectroscopy results indicated that the chemical composition was also in specification, noting, however, that this technique is not entirely accurate for Carbon or for trace elements in small wt%. From the microscopy images collected, it was clear that there was anisotropy based on rolling direction and cutting from the plate. Optical profilometry showed that sandblasting operations performed before applying the coatings, introduced roughness and surface defects; the peak to valley distance in the surface of the specimens increased by nearly seven times with respect to the baseline material.

The tensile tests seemed to prove that plasma treatment had only small effects on the material strength or hardness when compared to sandblasted samples (values remained within standard specifications). Orientation and standard testing error inherit in mechanical testers was greater than any change from the sandblasted to the post-plasma treated samples. Orientation also did affect individual samples, but it did not have a consistent effect for all strength tests. The two plasma treatment equipment types evaluated were effective at removing the coatings from the areas treated and could certainly be used to remove all the painting systems employed. The mechanical properties of the alloy underneath the coating remained within the MIL standards after the treatment.

Recommendations for Further Research

We recommend conducting studies with a greater number of specimens, since the current effort employed a very limited number of specimens for each variable studied: Only 3 machined tensile specimens and 3 sandblasted ones served as baseline. Two samples were tested for each coating type (8), orientation (2), and plasma technology (2). That is, only two data points were taken for the exact same set of variables. The study comprised a total of 6 baseline samples and 64 post-plasma specimens.

NPS-20-N022-A: Corrosion Testing of Cold Sprayed Coatings and Deposits in Simulated Austere Marine Environments

Researchers: Dr. Andy Nieto and Mr. Troy Ansell
Student Participation: LT Latriva Johnson USN

Project Summary

Cold dynamic gas spray, better known as cold spray, has generated much interest for repairing metallic components and depositing protective metal coatings. Naval shipyards recognize the potential of this technology to provide rapid repair and manufacturing capability and to replace welding as the state-of-the-art for metal joining and repairs. A relative unknown is the relationship between structural performance and corrosion resistance of the cold sprayed deposits. Corrosion resistance is critical to marine applications, and it is necessary to know how the thickness of a coating (which affects cost and deposition time) affects its corrosion resistance. In this study, composite Al-Al_2O_3 coatings of varying thicknesses were deposited on HY100 steel substrates using an in-house, cold spray facility. The coatings were evaluated in a salt fog chamber for 1000 h in accordance with the ASTM B117 standard. Mass and thickness measurements appear to indicate no fundamental change in the corrosion behavior; weight gradually increases across all coatings with relatively insignificant variations. However, pitting corrosion affects the variable thickness of coatings differently. The thinnest coating (~100 μm) is significantly deteriorated, with some areas retaining only remnants of the coating. The middle coating contains pits that traverse over half of the thickness. The pitting in the thickest coating is least severe, relative to the others. The study appears to indicate no fundamental change in corrosion behavior with coating thickness. Instead, thicker coatings perform better due to there being more deposited material available to protect the substrate. Regular inspections of cold spray deposits are needed, with thinner coatings needing much more frequent maintenance intervals to ensure integrity of the coating is maintained.

Keywords: *cold spray, corrosion, salt fog, protection, repair*

Background

The Navy is interested in developing and implementing technologies that can be used for repair and protection operations at the site of need, such as naval shipyards or ships at sea. Cold spray is an emerging technology utilizing relatively low temperatures (compared to welding and other conventional metal working techniques) for the deposit of metallic deposits or coatings. The process requires a metallic feedstock (e.g., metallic powder particulates) and a high-pressure gas to accelerate the metallic particulates to supersonic speeds, which enables them to impact the surface with sufficient kinetic energy to adhere onto the material and form a continuous deposit, layer by layer. Such coatings can be used to provide protection from wear and corrosion. Similarly, cold sprayed deposits can be used in the same manner as conventional welds, to repair and join metallic structures. Welded deposits often cause damage to the underlying metal, often exacerbating underlying materials and corrosion related issues. The relatively low temperatures used in cold spray allow temperature-sensitive substrates (e.g., steel, magnesium, Cu-Ni alloys) to be sprayed without damage to the substrate. The cold sprayed deposits themselves exhibit excellent mechanical properties because of the strengthening imparted by the severe plastic deformation (i.e., work hardening) that the metallic powder particulates undergo during the deposition process. What is unknown, is how durable these deposits will be when in service in an austere marine environment, such as that experienced on a Navy ship or in a seaside shipyard or port. Cold sprayed deposits may exhibit corrosion behavior distinct from either welded or bulk metals due to their unique structure. Cold sprayed deposits consist of dense stacks of metallic layers; such interfaces may become sites for corrosion.

Findings and Conclusions

The objective of this study was to test cold-sprayed deposits of varying thickness on HY-100 steel substrates in a simulated austere marine environment, according to ASTM standard B-117-11 using the salt fog chamber facility at the Naval Postgraduate School. Cold spraying parameters were modified to obtain a thin coating of approximately 100 μm, a middle coating of approximately 600 μm, and a thick coating of approximately 2.5 mm. The thin coating was intended to be on the lower end of the coatings that might be utilized by naval shipyards for repair applications. The upper tolerance limits for cold sprayed coatings on the naval shipyard at Pearl Harbor are about 750 μm, so the middle coating was just shy of that upper bound. The thickest coatings were intended to demonstrate the potential for using cold spray as bulk repairs and even fabrication of structural loadbearing deposits. Understanding the role of coating thickness on corrosion is important to end users and their applications, such as repair operations in a shipyard, because depositing thicker coatings requires more material usage and fabrication time.

The study will generate new knowledge on a parameter-performance relationship in cold spray that has received very limited study. Only one study has investigated the effect of cold spray coating thickness on corrosion behavior. The study utilized electrochemical measurements and indicated that protective passive behavior was observed in 316L stainless steel, cold sprayed coatings when the thickness was greater than 100 µm. This coating thickness also corresponds to the thickness of the thin coatings in the present study, albeit the current study uses aluminum-based coatings and not iron-based coatings.

The current study will evaluate the cold sprayed coatings of varying thicknesses under simulated austere marine conditions using a continuous salt fog exposure. Salt fog chamber tests were conducted for over 1000 h (continuous) to gauge the durability and corrosion behavior of the deposits. Coating corrosion behavior was investigated by measuring the cold spray coating material recession and the thickness of corrosion products. Weekly measurements of specimen mass and thickness were measured. Thickness measurements were across three points and an average taken. After 1000 h, all three coatings experienced consistent increases in mass and thickness. However, cross-sectional analysis appears to indicate the pitting corrosion is severe and most of the thin coating is degraded and consumed, leaving the bare HY100 steel directly exposed to the salt fog. Visual examination shows severe rusting and corrosion of the bare substrate as a result. The middle and thick coatings exhibit deep pits, traversing half of the middle coating's thickness. The penetration of the coating, likely, will accelerate corrosion greatly, as the electrolyte (salt fog) is then in direct contact with metals with a significant galvanic potential mismatch. Initially, there will be a large anode to cathode ratio, where the pitting aluminum is the anode and the exposed HY100 steel at the tip of the pit will be the cathode. As the pit grows and more HY100 area is exposed, the anode to cathode ratio will decrease and accelerate corrosion. Initially, effects of galvanic corrosion are only seen at the edges of the coating where the substrate and coating material are in contact and exposed to the electrolyte.

Additional tests lasting 2000 h are underway to see the evolution of corrosion products, mass changes, and substrate integrity over time. However, initial results indicate that under a severely corrosive environment the coating thickness must be sufficiently thick to prevent pitting corrosion from penetrating across the thickness. The results suggest that there is no threshold for a coating's thickness that significantly alters its behavior. The mass gain measurements are relatively consistent across all coatings. If passivity were reached at a critical thickness, the nature of the corrosion attack would fundamentally be altered.

Recommendations for Further Research

Parallel studies using other substrates of naval interest (e.g., Cu-Ni), and other coatings with good corrosion resistance (pure Al) are underway and will shed some light on the role of coating thickness on corrosion behavior and whether the basic corrosion behavior and response changes after some threshold. In light of understanding the basic corrosion response, additional chemical analysis will be conducted to identify the corrosion products as they shed light on the chemical reactions at play during the anodic dissolution of the coating material itself. The results of this study indicate that cold spray coatings used in marine environments must be regularly inspected and possibly maintained with additional cold spray layers. Once a pit traverses the coating's thickness, corrosion accelerates due to the increased contribution of galvanic corrosion and to the small anode to cathode area effect. Galvanic mismatch can, of course, be overcome by spraying coatings with minimal galvanic potential mismatch.

NPS-20-N131-A: Operational Flexibility of Multi-mission Interceptors (HVP)

Researchers: Dr. Eugene Paulo, Dr. Paul Beery, and Dr. Wayne Porter CAPT USN Ret.
Student Participation: Kayla Rhynes CIV, Tamika Richardson CIV, Daniel Millican CIV, and Salvatore Licci CIV

Project Summary
This project explored how a common hypervelocity projectile (HVP) munition could support Anti-Air Warfare (AAW), Anti-Surface Warfare (ASUW), and Naval Surface Fire Support (NSFS) missions by comparing the legacy munitions to the HVP fired from U.S. legacy weapon systems. This study examined the effects of HVPs in mission planning, logistics and use in multiple mission areas. The main objective question for the study was, “Will the use of HVPs in legacy weapon systems provide equivalent offensive and defensive capability and improve logistic operations in mission planning?” Using model-based systems engineering and architecting, the project formalized the criteria needed to perform a quantitative systems analysis for the operational, or mission, flexibility inherent in the HVP system. An in-depth model was created that analyzes the performance of multiple variables in the scenario for both the inclusion and exclusion of the HVP munition, which provides information of the overall effectiveness. The results provide evidence of the benefit of incorporating the HVPs into the weapon systems load out. There are benefits in cost, resupply, and munitions available, while maintaining performance. Based upon the results of this modeling, the initial hypothesis was confirmed that the effectiveness of HVP munitions improve the overall mission success, as well as deliver a cost effective alternative to using only legacy weapon systems.

Keywords: *operational effectiveness, high velocity projectile (HVP), multi-mission planning*

Background
This study examines the effects of using HVPs as a common munition in the MK 45 – 5-inch gun onboard the DDG 51 (Arleigh Burke) and CG (Ticonderoga) class naval ships, and the Advanced Gun System (AGS) 155mm guns onboard the DDG 1000 (Zumwalt) class naval ships as a multi-mission munition. Missions of interest include ASUW, AAW, and NSFS. The chemically propelled HVP munition provides multi-mission flexibility allowing the warfighter to leave port with a deeper magazine load-out than with just conventional missiles (Fisher, 2019).

Regarding AAW missions, recent research indicates that two primary concerns in defending against anti-ship cruise missiles (ASCMs) or unmanned aerial vehicles (UAVs) are limited magazine depth and cost of missiles (O’Rourke, 2020). The first issue refers to the amount of munitions that a DDG or CG can carry for both defensive and offensive purposes. All three classes of ships (Arleigh Burke DDG, Zumwalt DDG, Ticonderoga CG) rely on surface-to-air missiles (SAMs) and close-in weapon system (CIWS) guns for defense against threats, and either the MK 45 or AGS and tomahawk land attack missiles (TLAMs) for offensive strike. Both the SAMs and TLAMs utilize the MK 41 VLS cells. This degree of commonality allows for a limited degree of operational flexibility (i.e., a more defensive or offensive posture, or a balance between each posture with the limiting factor being the magazine limit of each ship). Should the mission change while underway and the munition load-out not support the new mission needs, a resupply at sea or in port would be required, delaying a response, or causing a temporary withdrawal from the area of operations.

The second issue is the cost of a current legacy SAM to shoot down an enemy manned aircraft, ASCM, or UAV. Currently, this can cost potentially more than a million dollars per missile, which may be considered acceptable in situations where only a few SAMs are needed to save the lives of Navy Sailors and Naval assets. However, in situations where our adversary can launch swarms of attack aircraft, ASCMs, or UAVs, the cost approaches a prohibitive cost exchange ratio. Both issues will require operational changes as well as new capabilities to maintain the Navy's maritime superiority.

The HVP munition may improve logistics operations of a Naval Expeditionary force composed of DDG and CG ships by alleviating mission-specific weapons configuration for defensive and offensive missions. Deploying HVP munitions to the fleet could give these ships increased capabilities and offers a more practical and cost-efficient alternative to building or refitting ships with electromagnetic railguns and their associated energy support systems.

Findings and Conclusions

The specific mission scenario focuses on the Pre-Assault Phase of an Operation to Neutralize a Threat to Navigation Posed by Enemy-Held Island. An adaptive force package (AFP) has been formed to seize control and neutralize threatening offensive capabilities and a small contingent of enemy forces located on strategically important Red Island. The AFP consists of an amphibious ready group (ARG) gaining sea control of surrounding waters, and neutralizing threatening shore installations prior to an amphibious assault. An operational model was built using ExtendSim to simulate the pre-assault phase of the operation and allow for systems analysis.

Microsoft Excel was used to create a stochastic model which explores the implementation of HVPs in a defensive or offensive engagement against an adversary that might have weapon superiority. The scenario was modeled as a static version through the range target graph and the stochastic model. These tools were used to give an estimation of the number of missiles launched, HVP rounds fired, and a statistical outcome of our scenario. The results from analysis using our ExtendSim model, which were analyzed using Minitab, allowed for the ability to validate the data captured by the stochastic model. This enabled the team to calculate the measures of effectiveness (MOEs) and measures of performance (MOPs).
The analytical results provide evidence of the benefit of incorporating the HVPs into the weapon system load outs, to include benefits in cost, resupply, and munitions available while maintaining performance. The average total cost of a mission in the scenario used for this project without the use of HVP rounds is $487M. The average total cost of a mission with HVP rounds included is $397M. This provides clear evidence on the financial benefit of using HVPs in conjunction with the legacy weapon systems. Furthermore, incorporating HVPs into the weapons system load out decreased the number of resupplies needed for nearly every missile type for each ship. Thus, the inclusion of the HVP weapon system has proven that it will increase the legacy weapon systems' magazine depth and the total amount of munitions available.

The HVP munitions also maintained the legacy system performance. The AFP survival for the HVP weapon system in comparison to the use of only legacy weapons was practically equivalent with a difference of 0.06 percent. Overall, there was a minimal difference in performance based on the survival rate of the friendly forces. Additionally, it is clear to see that the enemy ships and land targets neutralized by the legacy weapons when the HVP is disabled is practically the same as when the HVP is enabled. Although roughly 99% of the enemy ship and land targets were defeated, whether or not HVP munitions were included, analysis concluded that mission effectiveness was enhanced through cost savings, storage capacity and related safety considerations. Each of these confirmed the initial hypothesis that HVP munitions provide an effective, cost-effective, and more flexible alternative to using only legacy weapon systems.

Recommendations for Further Research

Further research should consider creating a risk analysis of the incorporation of the hypervelocity projectile (HVP) munitions. This will enable the DoD to have a certain level of confidence in the HVP munitions after evaluating any potentials risks that the integration would entail. It is also recommended that HVP munitions be incorporated into the current load out within the fleet after conducting a risk analysis. The Navy will also need to continue pursuing new capabilities that can be implemented on existing ships in order to meet new threats from our adversaries.

In the future, it would be valuable to also conduct research into the effectiveness of salvos of HVP and heterogeneous weapon systems. This information will enable a new realm of possibilities of the U.S. military capabilities. In addition, it would be useful to recreate this study on a classified level with more specific parameters and adversary information. Overall, there are many ways the HVP munitions can be utilized to enhance the current capabilities.

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NPS-20-N134-A: Railgun Capability on Amphibious Ships

Researchers: Dr. Eugene Paulo, Dr. Paul Beery, and Dr. Wayne Porter CAPT USN Ret.

Student Participation: Nelson Ciron CIV, Adam Drake CIV, Allan Guess CIV, and Caleb Schulte CIV

Project Summary

An electromagnetic railgun (EMRG) is a high-velocity, long range armament that can fire projectiles at approximately seven times the speed of sound by utilizing electromagnetic propulsion instead of a conventional missile weapons system that relies on a chemical propellant. The accuracy and lethality of the EMRG weapon could provide better operational effectiveness when conducting naval missions. This project investigated the effectiveness of an EMRG equipped San Antonio-class ship as part of an amphibious task force (ATF) conducting littoral operations in a contested environment (LOCE). This effort furthers the research into Expeditionary Advanced Base Operations (EABO) by establishing the EMRG equipped amphibious ship as a hub of activity capable of coordinating amphibious assaults upon an enemy shore. Five courses of action (COAs) were simulated to demonstrate the possible force structures available to naval commanders, including one COA without an integrated EMRG (COA 1 requires an escort destroyer) and four conceptual COAs that utilize the EMRG in various ways. Three levels of enemy force strength were designed (low, medium, high) to produce a spectrum of ATF performance outcomes for each COA. Analysis of the simulation results showed that cycle time, various probabilities of hit, number of EMRGs, firing scheme, and initial ATF standoff distance are the most significant factors that influence the performance of the EMRG against medium and high enemy concentrations in the objective area. The addition of the EMRG improved the performance and survivability of the ATF when conducting the amphibious assault mission.

Keywords: *amphibious assault ship, hypervelocity projectiles, railgun*

Background

In conjunction with the LOCE concept, the U.S. Navy and Marine Corps are in the process of developing the concept of EABO (Berger, 2019). This conceptual operation schema gives Marines the ability to conduct mobile and distributed operations to provide fires, targeting, electronic warfare, and ground support in a contested environment (Clark & Walton, 2019). The expeditionary advanced bases (EABs) can be sea-based command ships or forward operating bases on shore or inland. The EABs need sufficient defensive capability to withstand fires employed against them. The EABs are crucial in the development of future operational concepts for amphibious operations, and the utilization of current and future weapon technologies may influence future naval and joint operation force planning.

Weapons aboard standard amphibious ships range from close-in weapon systems (CIWS) to expensive missiles that have effective ranges of less than 50 nm. Naval and joint operations have been investigating the technology and scientific principles of an EMRG as a promising materiel solution that can launch low-cost GPS-aided projectiles at great distances and speed (O'Rourke, 2019). The EMRG is expected to provide a multi-mission aerial defense and naval surface fire support (NSFS) capability by the 2030 timeline.

The operational goal of the ATF is to successfully deploy the landing force to the shore with minimal loss. It is critical to the mission that these boats and the vertical lift platforms can reach the shore multiple times without being destroyed by the enemy's established littoral and land denial capabilities. To accomplish this goal within the established EAB, the ATF must be able to defend itself against numerous enemy threats, including anti-ship cruise missiles, medium-range ballistic missiles, drones and drone swarms, small boats, small-arms fire, aircraft, and ground artillery (stationary and mobile). Currently, the ATF is equipped with a variety of weapons systems able to engage the enemy forces at various distances. The integration of the EMRG capability on the San Antonio-class ship may allow sustained and high operational-tempo fire support at targets that are positioned over the horizon. This added capability may also allow for the amphibious ship to have a larger range of potential stand-off distances from the enemy, helping to decrease its vulnerability to shore fires.

This research focused on modeling and evaluating the operational benefits and mission effectiveness of an EMRG-equipped San Antonio-class ship while it performs an amphibious assault. The long-range capability of an EMRG was investigated for use in landing site preparation support, deep-strike NSFS to expeditionary land forces, and anti-air defense. The EMRG has the potential to engage and eliminate enemy targets from a much greater distance than traditional artillery pieces offering the potential benefit of increased ship survivability. Multiple configurations of the EMRG and ATF composition were compared and analyzed to determine the potential benefits of using an EMRG-equipped San Antonio-class ship.

Findings and Conclusions

The research approach closely follows the principles of mission engineering, where the overall mission objectives drive the design process. In this method, all of the design, planning, and integration activities of the individual system capabilities directly relate to the overall performance of the mission. A recent article highlighted the use of Model-Based Systems Engineering (MBSE) concepts as a modern approach to the mission engineering process that could be applied to architecting and design of a system in relation to the overall mission (Beery and Paulo, 2019). In order to formally merge mission engineering and MBSE into a systems engineering process, the research team applied a tailored Vee model that maps the systems engineering process elements to the development of a “mission system” (including both operational and system modeling) which addresses the potential capability that an EMRG-equipped San Antonio-class ship may add to the execution of that mission.

The primary objectives of this research were to determine the following:

Does the increased range and firing rate of the EMRG provide an operational advantage over current ship-board weapon systems? Does the increased magazine depth of the EMRG provide an operational advantage over current ship-board weapon systems? What design, or tactical, characteristics of the EMRG are most significant to improving the operational performance of the ATF in the amphibious assault mission?

The measures of effectiveness and performance of the ATF were based on the probability of regaining control of the island (defined as destroying all enemy targets), percentage of intercepted enemy missiles, and survivability of the ATF. Five COAs were simulated to demonstrate the possible force structures available to naval commanders, including one COA without an integrated EMRG (COA 1 requires an escort destroyer) and four conceptual COAs that utilize the EMRG in various ways. The five COAs vary in ATF configuration to explore the performance of the EMRG by calculating the results based on the effectiveness and performance measures when conducting the amphibious assault mission. Three levels of enemy force strength were designed (low, medium, high) to produce a spectrum of ATF performance outcomes for each COA.

Analysis of the simulation results showed that cycle time, number of EMRGs, and initial ATF standoff distance are the most significant factors that influence the performance of the EMRG against medium and high enemy concentrations in the objective area. Additionally, one of the most influential factors in the simulation was the accuracy and precision of the EMRG weapon against various target types, such as enemy missiles, ground targets, and aircraft. The EMRG fires a global positioning system (GPS) aided projectile that can adjust mid-flight to guide the round more accurately to its intended target by using control fins. The advancement of this technology will greatly increase the performance of the weapon and resulting operational effectiveness because of the emphasis on successful hits seen in the simulation analysis and design of experiments.

Recommendations for Further Research

The research indicates that the addition of one or more electromagnetic railguns (EMRGs) to an Expeditionary Advanced Base launched task force will achieve amphibious assault objectives with swifter, cost-effective, and sustainable attacks from a weapon capable of over-the-horizon attacks against a range of enemy targets. Although the EMRG is still under development, this new technology introduces a new long-rang capability that is precise, lethal, and capable of sustainable rapid fire against enemy targets. However, there are several considerations for further research.

First, more realistic and mission-specific data inputs will provide more accurate and precise results for the performance of the amphibious task force but pushes the simulation potentially into classified distribution categories. Our study used simulation inputs reviewed by subject matter experts in the field of naval combat and the EMRG development and were sufficiently realistic to allow for insight and provide a close approximation of the imitated encounter. Nevertheless, future research should include classified data and therefore be conducted in a classified setting.

Additionally, integration of the EMRG into existing naval ships will require thorough design planning that considers space and weight allocations of the EMRG and all of its subsystems including autoloading, rail cooling, munitions storage, and energy generation and storage. These developmental concepts and technology requirements are necessary for the maturation of a promising naval EMRG weapon. A significant limiting factor to the widespread use of this weapon is the power generation requirement, energy storage, cooling, munition auto-loading, rail reliability, and maintenance required to operate the weapon system. Likewise, the number of rounds available on the ship and the ability to load at sea will improve the performance of the EMRG by ensuring sufficient availability for mission loadout. creating a situation where projectiles may be expended prematurely in the mission.

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NPS-20-N143-A: Effectiveness of Hypervelocity Gun-Based Defense

Researchers: Dr. Paul Beery and Dr. Eugene Paulo
Student Participation: John Means CIV, Christopher Quarles CIV, Miguel Sanchez CIV, and Matthew Wu CIV

Project Summary
This project conducts a mission engineering focused analysis of the effectiveness of a hypervelocity projectile (HVP) used to supplement existing capabilities for gun-based defense. The analysis is based on an adaptive force package (AFP) conducting a fires mission. The AFP utilizes the HVP in conjunction with existing missile and gun-based systems currently fielded on Arleigh Burke and Ticonderoga class ships. A simulation model is constructed that compares a baseline configuration (without HVP utilization) to various integrated HVP configurations—some rely entirely on HVP utilization while others reduce the loadout of existing weapon systems and utilize the HVP as a solution to mitigate the impact of those reductions. Analysis results indicate that the HVP can increase the combat capability of the AFP if employed as a supplementary capability aligned with existing systems. Results indicate that the HVP provides minimal performance gains in scenarios where the incoming threat is relatively small (less than 50 targets). When the incoming threat is increased to approximately 100 targets, the HVP provides an operationally relevant improvement to AFP survivability. In addition, a cost analysis indicates that the HVP provides a net decrease in the cost to defend against enemy salvos of all sizes. From an operational employment perspective, the analysis suggests that further development of the HVP should prioritize reducing the cycle time between fires rather than probability of an individual round hit.

Keywords: *hypervelocity projectile, HVP, model-based systems engineering, mission engineering, adaptive force package, modeling and simulation*

Background
The HVP, currently in the early stages of system development, is designed to provide multi-mission capability as well as the flexibility to fire using either conventional ship-based guns or future electromagnetic weapons. Of particular interest is the potential utility of the HVP as a capability multiplier in naval gun-based defense. Gunzinger and Rehberg (2018) provide specific context, noting that ballistic missile defense often becomes a salvo competition where numerical advantages may overwhelm technological advantages. Moreover, ballistic missile defense generally relies on layering of defense assets using a combination of counter ballistic missiles and kinetic interceptors. Given that any naval force is going to be inherently constrained in terms of force size, the HVP may provide additional flexibility in development of future operational concepts. The supersonic speeds and mid-air course correction capabilities of the HVP make it well suited to expand existing capabilities.

This project investigates the role of the HVP as part of an AFP employing currently fielded systems. Specifically, the HVP is modeled as part of gun-based defense using Mk 45 five-inch guns on Arleigh Burke class destroyers and Ticonderoga class cruisers. The Arleigh Burke class destroyers are equipped with one Mk 45 five-inch gun and two Vertical Launch System (VLS) units that carry Standard Missile-6 (SM-6), SM-3, SM-2 Medium Range (SM-2MR), Enhanced Sea Sparrow Missile (ESSM), Vertical Launch Antisubmarine (VLA), Tomahawk Land Attack Missile (TLAM), and Harpoon missiles. The Ticonderoga class cruisers are equipped with two Mk 45 five-inch guns and SM-6, SM-2 Extended Range, SM-2MR, ESSM, SM-3, TLAM, VLA missiles, and Harpoon missiles. While multiple candidate designs of the HVP are being proposed, some of which may be fired from multiple systems, this project focuses solely on the operational utility of the HVP fired from the Mk 45. This focus provides two benefits: first, it focuses on an operational strategy that could be employed as soon as the HVP is technologically mature enough for deployment. Second, it allows for mixed-magazine strategies that do not require additional propellants or compromises with respect to existing magazine depth.

This project assumes a concept of operations (CONOPS) where a blue force utilizes existing munitions aboard the Arleigh Burke and Ticonderoga classes and defends itself against a salvo of anti-ship missiles. That CONOPS is expanded into four different scenarios that examine different operational implementations of the HVP. First, a baseline scenario is modeled where the HVP is not utilized. The second scenario utilizes the HVP to augment the defensive capabilities of long-range defensive missiles; the third utilizes the HVP to augment medium-range missiles; and the fourth utilizes the HVP as the primary munition.

Findings and Conclusions

This project utilizes a simulation model to examine the operational utility of the HVP. The simulation model examines four distinct permutations of the CONOPS. Within each of these scenarios, the specifics of the layered defense strategy were altered. The baseline option does not utilize the HVP. The second utilizes the HVP to augment the SM-6 and SM-2 as a long-range munition while reducing the assumed loadout of both SM-6s and SM-2s by 50%. The third utilizes the HVP to augment the ESSM as a medium-range munition while reducing the loadout of the ESSM by 50%. The fourth eliminates all existing munitions and solely utilizes the HVP for ship defense. In each case, the priority of fire scheme is varied, a full description is available in (Means et al., 2020). The model is built using ExtendSim, a discrete event simulation program that allows for the development of multiple engagement envelopes that incorporate the distance between platforms, enemy platform speed and type, and AFP platform weapon selection and speed. This sequence was implemented as a multi-step simulation in which threats are generated, weapon assignment choices are varied, engagements are modeled, re-engagement is employed as needed, and data regarding AFP survivability and effectiveness of the defense system is collected.

Data was collected for each of the permutations of the CONOPS. In each of the permutations, four different salvo sizes were considered: 25 threats, 50 threats, 75 threats, and 100 threats. In the baseline configuration, which does not utilize the HVP, the AFP is able to destroy over 95% of incoming targets for the 25- and 50-threat salvos; however, the performance drops to 88% for a 75-threat salvo and 78% for a 100-threat salvo. This suggests that current munitions loadouts are well suited to smaller salvo sizes and that the HVP may improve operational effectiveness for larger salvo sizes. Examination of CONOPS that utilized the HVP confirmed that it may improve operational performance but is subject to several employment and design considerations. The model varied both the assumed probability of hits for HVP rounds from 10%–30% and varied the number of HVP rounds fired at each target from three to five. The results suggest that incorporation of the HVP improves performance in the 75-threat salvo case regardless of the individual round probability of hit (provided it is at least 10%) or the number of rounds fired (provided at least three rounds are fired). Subject to those constraints, employment of the HVP increased the percentage of targets destroyed from 88% to 96%. The HVP offers a similar performance benefit for the 100-threat salvo case; however, the performance gain is smaller if the individual round probability of hit is less than 20%. In all cases, the systematic reduction to the number of SM-2, SM-6s, or ESSMs employed resulted in a sharp decrease to overall performance, suggesting that, even when supplemented by the HVP, the existing systems are operating at full capacity and decreases to missile loadouts cannot be mitigated through employment of the HVP.

Recommendations for Further Research

This project conducted an operational analysis of the utility of the hypervelocity projectile (HVP) as an enabler of gun-based defense for an adaptive force package (AFP). The modeling and analysis show that the HVP can increase the combat effectiveness of an AFP, if employed correctly as part of a layered defensive effort in conjunction with existing systems. The research shows that the HVP provides limited operational benefit in smaller engagements where the enemy salvo size is less than 50 combined targets. The HVP provides up to an 8% improvement in enemy salvo destruction for enemy forces up to 100 combined targets, subject to a final system design that realizes an average probability of hit of at least 20% and an employment strategy that fires five HVP rounds at each potential target.

The modeling and analysis conducted as part of this project can be expanded in several notable ways. First, the utility of the HVP can be examined in alternative operational environments. This project focused on a generic defense scenario with substantial assumptions regarding the number of both friendly and enemy platforms, as well as assumptions regarding environmental conditions. Alterations to any of those areas may impact the findings in this report.

The U.S. Navy is currently examining alternative missile loadouts aboard both the Arleigh Burke destroyers and Ticonderoga cruisers considered as part of this project. Subject to the finding in this project that a reduction to the number of Standard Missile-2s (SM-2s), Standard Missile-6s (SM-6s), and Enhanced Sea Sparrow Missiles (ESSMs) carried aboard each of those ships classes may negatively impact the probability of enemy salvo destruction, it would be worthwhile to investigate alternative compositions of missiles aboard both ship classes, either in terms of total missile loadout or percentage of total missile composition. Additionally, there is currently an interest in employing the HVP in conjunction with the electromagnetic railgun, rather than the existing 5-inch gun systems. That may change the performance characteristics of the HVP and allow for additional opportunities to change the missile loadouts of any associated ships.

Finally, although there is an initial cost estimate presented in Means et al.'s report (2020), there is a need to conduct a complete logistics life cycle cost estimate for the HVP. Classification, technological maturity concerns, and data access issues prevented a more holistic cost estimate from being conducted as part of this project.

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NPS-20-N146-B: Commercial Batteries for Navy Use

Researchers: Dr. Ira Lewis and Dr. Kenneth Doerr
Student Participation: No students participated in this research project.

Project Summary

We reviewed the state of the global battery industry, and made recommendations for collaboration among Navy organizations, and suggested potential contracting mechanisms that might enhance the Navy's effectiveness in working with the battery industry. This included a literature review of industry developments and an analysis of relevant Department of Defense acquisition policies. The Naval Sea Systems Command and other Navy organizations created the Naval Battery Development and Safety Enterprise in 2018. This Navy initiative is supported by research that has found that information sharing and an increase in market knowledge about suppliers leads to more informed contracting decisions that result in better outcomes. These contracting decisions are tightly interrelated with engineering, logistics, maintenance, and financial considerations. This project seeks to assist the Navy by identifying key battery industry trends and potential approach for working with the industry. The study's purpose was to identify the principal trends and issues associated with the global battery industry and develop recommendations for how the Navy could work with the industry to meet the Navy's long-term needs.

Keywords: *batteries, lithium-ion, acquisition, industrial base*

Background

The Navy buys a wide variety of consumer, industrial, and military-specific batteries. Developments in battery technology are providing significant improvements in performance, weight, size, and reliability. Together, these factors will contribute to increasing the Navy's warfighting capabilities, particularly with increasing power demands of emerging weapon systems like high-energy lasers. Surges in military activity may also lead to large increases in the quantities of batteries requisitioned by deploying and deployed forces.

Findings and Conclusions

We did not locate any previous research on how the U.S. government carries out battery acquisition. The study found that military customers represent only a small part of the global demand for batteries, and that domestic suppliers would benefit from a long-term approach by the Navy that goes beyond lowest-cost procurement based on short-term requirements. We suggested some existing contracting authorities that might support an enhanced approach to working with the battery industry. In that vein, the Naval Battery Development and Safety Enterprise could offer a basis for a more collaborative approach within Navy organizations and with the Defense Logistics Agency that might permit improved long-term results in acquisition of batteries such as cost, performance, and reliability. We did not suggest any changes to current legislation or regulations.

Recommendations for Further Research

The Navy would benefit from further exploration of the contracting mechanisms available, including industrial base funding, that would assist in meeting long-term battery technology development, security of supply, and cost and performance goals.

NPS-20-N186-A: Decoupling the Engine from the Engine Room

Researchers: Dr. Jarema Didoszak and Dr. Fotis Papoulias
Student Participation: No students participated in this research project.

Project Summary
Naval combatant ship design is plagued by the ever-present specter of changing mission requirements during the planning, construction and operational lifecycle of the vessel. The typical shipboard power systems load continues to grow at an increasing rate as a result of fielding high-power combat systems and a deliberate shift to predominately electrical over mechanical systems. In ship design, simply more available power is not the answer, rather power when it is required is the key. With the removal of services and systems supporting crewed operations, the Large Displacement Unmanned Surface Vessel (LDUSV) provides an unencumbered backdrop for investigation of the tradeoffs coming from decoupling of the prime mover (engine) and power production source from a fixed location within a common ship hull. By examining size, weight, and power (SWAP) versus mission power profile demand associated with traditional and emerging power systems, effects of power generation, distribution and storage are observed against ship design parameters. Operational benefits exist in customization of "installed" power regarding expectant power profile demand of the ship during a voyage. Decoupling the engine from the engine room facilitates optimization of power generation to meet the operational power requirement and provides flexibility in planning the mission set in terms of payload and on-station time. Further study is required in the areas of power connection interface, distribution and interchangeability of loadable power and fuel components and modules.

Keywords: *energy security, SWAP-C, adaptive shipboard systems, all-electric ship, alternative energy, compartment arrangement, flexible ship design, power configuration, ship design, shipboard power resources management*

Background
Traditional ship design is driven by hull form optimization. As a result, total resistance and, by extension, propulsion power selection are key attributes in the final design. Generally, allowances for detractors such as hull appendages, biofouling and other less predictable factors like variable environmental conditions, are accounted for when selecting the best available prime mover able to meet the contractual requirement. While this may make sense in the case of a vessel that is locked to its intended design draft and design speed, this is certainly not reflected in actual maritime operations. Moreover, naval vessels, unlike their commercial counterparts in the marine world, the latter of which are designed to maximize profit through optimization of performance, are often victims to "what if" scenarios and must be prepared to deliver performance across multiple, highly varied operational profiles. To further complicate this, the naval combatant ship mission is highly susceptible to the unpredictable, rapidly changing operational needs stemming from volatile political influences. These changes lead to an ever-growing need for more power-hungry mission systems such as lasers, railguns, and far reaching radars necessary to conduct the mission.

In order to meet the Navy's nominal goal of a 30-year surface ship hull lifespan with these uncertainties and variations in operational profile, alternate power schemes have been investigated by McCoy (2002), Doerry (2015), and others. Radial (conventional) power distribution and traditional (mechanical drive) power drives have given way to zonal distribution and integrated ship power systems. Reduction gear sets fixing the propulsion power train have moved aside to see the inclusion of motors driving propulsors. The intersection of these changes with flexible ship design have spurred the progressive notion that installed power need only be fixed at the point of sail versus the time of launch.

Previously, the Naval Postgraduate School (NPS) Total Ship Systems Engineering (TSSE) student design program developed a conceptual design for an LDUSV under the guidance of the investigators. The result was an unmanned, autonomous, long range, long endurance, multi-mission combatant, conceived to serve as fleet integrated force multiplier. The proposed powering scheme for the LDUSV consisted of hydrogen fuel modules and fuel cell (power) modules. The configuration that followed was envisioned to have no dedicated placement of the fuel storage and power modules, as to be completely interchangeable with traditional cargo modules used for mission equipment, storage and other payloads. This general approach was then expanded to more traditional powering solutions as well.

The notion of having no engine room resulted in a modular and scalable power source that could be tailored to the mission. With as few as one power module required, the remaining cells could be used for fuel, cargo or as open space. When requirements for high speed or high-power mission systems were necessary, the LDUSV would be configured with more power generation modules and fuel modules. This inherent flexibility provides operational commanders the ability to have a fleet of individually configured vessels all from the same common hull form, thus decoupling the need for a large, fixed engineering plant.

Findings and Conclusions

There is a desire within the naval engineering community to explore and assess new ways that energy systems can be designed and integrated onboard ship in order to expand their operational capability. While increasing power output efficiency for a given amount of installed power is desired, novel concepts that show benefit in the overall optimization and customization of delivered power matched to mission demand are the next step. To date, much of the research has been in understanding the power load requirement relationship to installed power. However, this somewhat static approach maximizes available power generation at the time a ship launches from the slipway.

Designed as an unmanned vessel, the LDUSV was a logical choice for this research as its conceptual design was scant on interior bulkheads and designated compartments. Without the need for traditional passageways to move personnel throughout the vessel, and a desire to maximize cargo payload and space, the idea of external access prevailed. This made the standard twenty-foot equivalent unit (TEU) a prime choice in the form factor for the power, fuel, and cargo modules to be used in this study. The assumption is that the TEU form factor will be used as the standard "module." The weight and center of gravity data for subunits fit into each TEU are approximated based on available technical data.

First, the highly diverse set of operational mission scenarios that drove the LDUSV design were characterized in terms of peak power, duration of demand, and periodicity. Diverse power requirements that varied from maximum power for sprinting runs, to long range endurance during transoceanic transits, to the ability to loiter on nothing more than a trickle charge and then bring high power demanding systems online from an inactive state nearly instantaneously defined the load. Since it was clear that a standard installed power configuration could not be optimized for all these varied mission profiles, this led the researchers to pursue unconventional power system components, configurations and arrangements.

Candidate power generation sources were chosen to meet the loading profiles. Installed power systems were compared with containerized hydrogen fuel modules and diesel generator sets. The SWAP for each of the configurations was compared along with available payload cargo. Reduced SWAP and increased payload volume were both regarded as advantageous. The modular power source was found to correlate to a greater power density as compared to installed power systems in most loading cases.

Additionally, survivability effects such as stability and flooding compartmentalization were investigated in the LDUSV via the Program of Ship Salvage Engineering (POSSE) and through use of other engineering tools. The sought-after weight stability that physical installation of large prime movers low in the ship typically provides was accounted for by module loads (dry ballast) or other payload cargo loaded deep within the hull to achieve a similar stability result. Flexibility in loading of mission systems as payload and perspective changes in compartmentalization were determined to be beneficial in meeting the overall ship mission.

Recommendations for Further Research

While the results supported the primary goal of better matching the power generation to power demand based on the interchangeability of power, fuel and payload modules, not all aspects of the typical ship design spiral were exercised. Use of the Large Displacement Unmanned Surface Vessel model did not include hydrodynamic effects resulting from changes in draft and projected speed. Structural impacts regarding the loading of the vessel were also excluded from this analysis. The rate at which power was supplied was not able to be accurately modeled and was excluded from the analyses. Additionally, the added cost involved with swapping out the modules, their maintenance and repair were not investigated, nor was downtime with regard to the ship power generation capability in order to meet mission success.

Though promising in concept, there are other items that require more detailed research in order to implement this approach to flexible power generation. Some critical areas that were not examined as part of this study were the sizing, configuration, standardization and adaptability of the power, cooling, plumbing and ventilation connections required for the standard twenty-foot equivalent unit sized power, fuel and payload cargo modules. The ease of connection of interfaces, loading and exchange of the modules, and ability to centrally control and monitor the operation of the enclosed units as part of the overall vessel will indeed influence the feasibility and cost of such an undertaking.

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NPS-20-N213-A: MDUSV ISR Mission Requirements, Equipment, and Force Structure

Researcher: Mr. John Audia, Dr. Emil Kartlov, Ms. Amanda Coleman, CDR Jason Hull USN and Dr. Chris Verlinden
Student Participation: No students participated in this research project.

Project Summary
Periodically it is prudent to "snap the line" to visibly mark the current state of autonomous maritime systems and associated technology as it pertains to Navy Intelligence, Surveillance, and Reconnaissance (ISR) mission requirements. Being cognizant of the push-pull relationship between technology and requirements, we must simultaneously revisit and revalidate those requirements. To ascertain the state and value of this broad group, it is necessary to conduct extensive cross correlated background research. The process is analogous to the challenge faced by research, development, testing, and evaluation program managers preparing to launch new research initiatives, which are plagued by unrealistic timelines and funding uncertainties. In this light, the initial section of this report is a methods study, which describes a method for technical generalists to rapidly educate themselves on a specific technical focus area, using the topic of autonomous maritime systems in Navy ISR.

After achieving a positive outcome, we further explored the value and direct application of medical research relating to artificial muscles and biometrics. From there, we overlayed the contributing value of the Naval Information Warfare Center – Pacific Intelligence Carry-on Program (ICOP); and talent from the Information Warfare Community (IWC) Navy Reserves as concept development enablers.

To keep up with the pace of an ever-evolving state of technology associated with autonomous, unattended, unmanned platforms, it may be time to consider cross-walking between the architecture of a platform to the architecture of a human. This report introduces a short discussion on the necessity to lean forward on the concept of comparing traditional Department of Defense (DoD) system and design architectures to human brain and body architectures, as a means of emulating the anatomy and functions of the human brain and body as an integrated autonomous system approach for future Medium Displacement Unmanned Surface Vehicle (MDUSV) ISR platforms.

Keywords: *architecture, autonomy, intelligence, surveillance, reconnaissance, artificial intelligence, information warfare, mission requirements, data analytics, human brain anatomy and function*

Background
Command, control, communications, computers, cyber, intelligence surveillance and reconnaissance systems, along with an extensive array of sensors are, in effect, extensions of the way personnel operating and managing mission requirements think and function. A maritime platform, along with the crew, deploy with intent: first and foremost, to accomplish the mission, with minimal risk and loss, while ensuring the protection and survival of the crew. It is possible that our existing DoD architectural designs and strategies may limit our ability to fully leverage the technological advancements in unmanned, autonomous, unattended systems and associated capabilities.

Extensive work has been done on the use of autonomous surface platforms such as the Sea Hunter for a variety of mission sets, including, but not limited to, surface warfare and anti-submarine warfare. In each of these cases, maritime ISR is a component but not the primary focus. Building on the work of previous Naval Postgraduate School studies, this report expands on the specific ISR applications of autonomous surface vessels and attempts to describe and synthesize the current state of the art in technology. Additionally, we examine the current and historical state of government investment in these technologies.

Our report explored direct and/or near-term ability to leverage two enabling resources. ICOP is one of the most open architectures, leveraging to the greatest extent, state of the art technology, covering a wide range of collective ISR mission sets and analytic tools and applications. The IWC Navy Reserves are rapidly rediscovering and evolving their role and contributions in cyber warfare, information warfare, including cryptologic community remnants and tradecraft from the Naval Security Group and electronic warfare.

What instigated combining those two elements together was that for a totally autonomous, unattended, unmanned maritime ISR platform to function, it requires an "ISR brain." Capitalizing on the technology and resources provided by the ICOP, along with talent and tradecraft of the Navy IWC Reserves, may inspire and enable artificial intelligence research and innovation.

Findings and Conclusions

The dataset gathered for this report contained approximately 900,000 files. The data focuses on tracking the development and acquisition of new technology by the US government. It includes foreign trade and import information related to technology, patents, peer reviewed publications, government funding, grants, contracts, and Small Business Innovation Research (SBIRs). For the purposes of this analysis, we applied the Pacific Northwest National Laboratory IN-SPIRE tool to the heavily curated SBIR dataset, and we applied the GOVINI decision science tool to the grants, contracts, and purchases datasets.

Data analysis software was utilized in the data aggregation, alignment, visualization, analysis, storage, and reporting. The predominance of the analytic work in this research report was focused on the ISR mission sets, both existing in support of fleet operations and envisioned ISR mission sets potentially enabled by advanced technologies and capabilities presented through the furtherance of MDUSV acquisitions and deployment.

Database management and data curation are a continuous challenge for the federal government. This is in part because there are legal mandates that records of government activity including spending and acquisition be maintained and made available to the public upon request. While these records are kept, the quality and accessibility of many of these databases is dubious at best. Many government-maintained databases contain data entry issues, typos, missing or incorrect data, corrupted files or content, and a variety of other problems. As a result of our technology review, we realized that significant advances in many of the technologies directly associated with DoD challenges were more heavily funded and invested in by non-DoD organizations and entities. This suggests a much larger presence of medical and biotech programs related to sensors than the ISR category.

In the medical community, there appears to be significant investment in command, control, communications as it pertains to vaccines. This is logical as to track, optimize, and account for vaccine distribution, one requires exactly the type of command and control, or common operating picture, one needs for traditional defense mission sets like managing enormous distributions of assets across a broad geographic area for a variety of different applications.

The new artificial muscles described in the report promise both biomimetic propulsion and acoustic translucence. They are based on 3D printable resin, microfluidic structures, and electrostatic actuation. If fully developed, they would produce a quantum jump in the stealth capabilities of soft unmanned underwater vehicles. The projected improvements in stealth then pose the question of their impact on and consequences to ISR operations employing such craft.

Recommendations for Further Research

While the research methodology used for this report was effective, it can be further developed in future work. We created a research methodology which is software and data agnostic, designed to allow program managers and broad subject matter experts to rapidly summarize massive amounts of literature to determine the state of a broad technical field. It includes three steps: gather potentially relevant data, perform exploratory data analysis to synthesize and analyze useful data, and derive results from analysis to answer the original hypothesis and inform future decisions. Other datasets or software packages could be inserted into the methodology as needed.

Biomimetic propulsion can offer significant improvements in stealth for unmanned underwater vehicles (UUVs), based on the avoidance of cavitation and on the biological-like acoustic signature of the motion. However, even biomimetic propulsion when based on traditional actuators, e.g., electromagnetic motors, would produce a recognizable sonar signal due to mechanical impedance mismatch between the low density of seawater and the high density of the materials of the propulsion system. The new artificial muscles promise both biomimetic propulsion and acoustic translucence. We believe that the first navy to build and use such craft would achieve an overwhelming advantage in intelligence, surveillance and reconnaissance (ISR) operations.

This report spurred a set of conversations and produced some potential ideas like the inclusion or creation of software defined “things.” As the need becomes greater than the level of response that can be provided, there will be a forcing factor to create a software defined solution. The eventual state of a truly distributed (semi)-autonomous force will require a commitment to the development of the next step beyond ‘automation’, artificial intelligence.

To further explore the technology and resources provided by the Intelligence Carry-On Program and the Navy Information Warfare Community Reserves, mobilization of a (selected) individual as a direct resource to the Naval Postgraduate School (NPS) for a period of 18–24 months is recommended. This individual would shepherd the technology growth and coordinate follow-on efforts to explore deployment options and facilitate future Information Warfare Community Rapid Response capabilities.

Given significant investment by the medical community in command, control, communications as it pertains to vaccines to track, optimize, and account for vaccine distribution, the DoD should examine what work has been done in algorithms for tracking things like vaccine distribution and see how they apply to traditional defense concepts of operations.

We should explore, comparatively, the similarities and differences between DoD platform architectures and human architectures to gain insight into how close we are to creating DoD platforms as deployed extensions of a human driven workforce. To what extent we can create and apply human brain-body emulation in Medium Displacement Unmanned Surface Vehicle ISR platforms is uncertain, but not unattainable. NPS should lead, facilitate, and participate in the creation of a DoD Platform and Human Brain-Body comparative architecture study. The study and report would establish the landscape of possibilities and intent for the future of autonomous unmanned, unattended platforms, across the DoD.

N1 - Manpower, Personnel, Training & Education

NPS-20-N133-A: Building Connectedness: Managing Tensions Between Individual Participation and Organizational Control in Online Workplace Communities

Researchers: Dr. Kathryn Aten and Dr. Judith Hermis
Student Participation: No students participated in this research project.

Project Summary
Online communities have become ubiquitous in the workplace; however, destructive behavior in such groups has led to negative consequences for many organizations. Tensions between individual participation and organizational control indicate that active management of such sites is required. Our research provides a better understanding of the mechanisms associated with managing enterprise social media (ESM) by drawing from recommended practices of industry and examining the practices of an exemplary Navy-affiliated online community.

Our research indicates that there are both employee and organizational benefits of using enterprise social media. For employees, ESM offers an opportunity for information sharing, free expression, and social connection. For organizations, ESM is a communication tool for supporting strategic interests, including improving corporate effectiveness and efficiency, increasing employee well-being and engagement, and strengthening the corporate culture. Because of these benefits, many organizations seek to encourage appropriate participation in social media.

To ensure that enterprise social media supports the needs of organizations and employees, organizations should provide legal, ethical, professional, and humanistic behavior standards and create and monitor governance mechanisms to encourage participation and manage conflict. There are five recommended control mechanisms for helping to ease the tensions between organizational control and individual participation. At a minimum, the Navy should establish clear and transparent policies and enforce them fairly. In addition, lessons from our case study and other high-profile sites indicate that successful management of organizational and individual tensions requires dedicated resources. Active moderators can help to manage conflict and reinforce the values of the organization by setting the tone of the conversation, reiterating site guidelines, and enforcing fair and balanced conversations. Formal and informal leaders, including site moderators, can also use their positions of authority to encourage participation and engagement in high priority social and strategic conversations. By joining in the conversation, leaders can help reinforce organizational values, encourage diversity of thought, and help foster a climate of open dialog and innovation.

Keywords: *codes of conduct, community guidelines, community standards, corporate culture, employee engagement, internal communications, internal social networks, online trust, social media, social media controls, social media governance, social media handbook, worker rights, workplace terms of service*

Background

Online communities have become ubiquitous in the workplace and many large organizations have developed tailored, proprietary, or private versions of public social networking software. Social media in organizations can foster information sharing, increased communication, and collaboration. However, destructive behavior in such groups has led to negative consequences for organizations and posed risks to individual and organizational security. Scholars suggest that social media integration in organizations is outpacing our understanding of these technologies and theories of how they change organizational processes.

The Department of the Navy relies on online communities for social support, information gathering, and connection. Destructive online behaviors can occur and can result in negative consequences. A high-profile example includes Marine United, in which the group veered drastically from its original purpose of support and became dominated with racial slurs, jokes about rape, and revenge porn. To prevent these negative behaviors and to support healthy online communities, N17 commissioned NPS to explore practices to create and maintain healthy Navy affiliated online communities.

Findings and Conclusions

This study answered two primary questions: "How has the Navy successfully created and managed a successful, healthy online workplace community?" and "What are current industry trends in ESM?" In particular, we investigated user motivations, the alignment of social interactions and organizational values, challenges/failures of a Navy online workplace community, challenges of industry leaders in managing tensions between participation and organizational control, and common industry practices for creating and maintaining healthy online workplace communities. The research protocol included interviews with group administrators and a critical incident diary of administrator actions. We also interviewed group participants to capture individual motivations and responses and spoke to industry subject matter experts to identify industry trends in creating and managing enterprise social media (ESM). The research team analyzed the data using thematic analysis supported by qualitative analysis software.

Key findings include drivers of participation in enterprise social media, common criteria used to manage internal social media, and recommended control and moderation mechanisms. In addition, we identify the tensions between organizational control and individual participations as evidenced by administrator interactions in the Navy group and made recommendations for managing other Navy social media sites.

These recommendations include suggestions for focusing the organization and actions that can be taken to support healthy online communication.

Recommendations for the Navy

- Reinforce organizational values.
- Ensure group diversity in moderators.
- Monitor and address unhealthy behaviors.
- Promote transparency.
- Allow controversy.
- Monitor and manage extreme conflict.
- Encourage engagement and connection.

Moderator actions

- Exemplify and reiterate organizational values in posts.
- Build inclusivity and encourage 'at risk' members.
- Create public rules and use them in decision-making.
- Ban anonymous postings of opinions.
- Support respectful disagreements through example.
- Escalate actions, break out marginal conversations.
- Seed conversations in support of organizational goals

This research highlighted the importance of governance mechanisms in helping to ease the tensions between organizational control and individual participation. At a minimum, the Navy should establish clear and transparent policies and enforce them fairly. In addition, lessons from high-profile sites indicate that successful management of organizational and individual tensions requires dedicated resources. Active moderators can help to manage conflict and reinforce the values of the organization by setting the tone of the conversation, reiterating site guidelines, and enforcing fair and balanced conversations. Formal and informal leaders, including site moderators, can also use their positions of authority to encourage participation and engagement in high priority social and strategic conversations. By joining in the conversation, leaders can help reinforce organizational values, encourage diversity of thought, and help foster a climate of open dialog and innovation.

Recommendations for Further Research

Enterprise social media is key to the internal communications of the Navy. It is a powerful tool for social support, information gathering, and connection. To create and maintain healthy Navy affiliated online communities, the Navy should first update their social media policies to support individual participation and organizational goals as defined in this document. Second, the Navy should develop plans for how they man, train, and equip moderators for these groups. Next, further research is needed on the role of bystander interventions in developing techniques that support healthy dialog on controversial conversations and provide opportunities for members to develop their leadership skills and for the organization to strengthen the Navy Ethos. Finally, special care should be taken to ensure that minority voices are heard and encouraged.

NPS-20-N191-B: Social Network Analysis, Connectedness, Intrinsic Motivation, and the Effect on Sailor Retention

Researcher: Dr. Gail Thomas
Student Participation: LT Autumn Gorden USN

Project Summary
The goal of this three-part project was to explore how network analysis could be used to understand the impact of Navy enlisted Sailors' personal, professional, and community networks on retention. Part A, led by thesis student LT Autumn Gordon, included focus group data paired with a questionnaire that were collected on-site at Naval Air Station (NAS) Lemoore to build egonet (personal network) profiles of enlisted Sailors. Results indicated that Sailors with high levels of job embeddedness, that is, Sailors who have strong ties to their organization and community, have strong levels of social support through a variety of local and non-local relationships both on-the-job and off-the-job. Conversely, Sailors with low levels of job embeddedness who desire to leave NAS Lemoore indicated a lack of social support from local and non-local relationships. Based on these findings, we recommend leaders focus on ways to help Sailors build local network connections to help increase retention. Leaders could encourage this by creating more opportunities for mentorship, knowledge sharing, and community and connection both on and off the job.

Part B employed Defense Management Data Center (DMDC) personnel data to construct social networks of a simulated enlisted Sailor community. In contrast to Part A, which considered individual (ego) networks, this part examined community-level networks. We found that network stability and diversity (e.g., gender, rank, ethnicity) influences reenlistment decisions. For instance, those who chose to leave were more highly connected to one another and less well connected to others than those who chose to stay. Based on these findings, we recommend leaders pair re-enlistment data with work group networks to understand how connections contribute to turnover and what types of commonalities are key to building robust communities.

Part C was an examination of the social network analysis methodology and its potential application to U.S. Navy talent management functions.

Keywords: *social network analysis, SNA, social relationships, social support, retention, turnover, job embeddedness, enlisted, Defense Manpower Data Center, DMDC, ego networks, affiliation networks*

Background
This study builds on a long line of research that has shown that an employee's turnover decision is influenced by one's position in a social network (Krackhardt & Porter, 1986), and that social connections with others have a significant influence on the decision to stay or leave an organization (Jo & Ellingson, 2019). For example, an employee who is more centrally located in the organization's network is less likely to leave because leaving would mean giving up one's social capital, or benefits associated with those connections (Lee et al., 2004; Borgatti & Halgin, 2011). Likewise, friendship networks are often used for social and emotional support, which are important for establishing belongingness and for weathering instability or personal hardships (Vardaman et al., 2012; Vardaman et al., 2015). Other actors who might

prove important are connections with a mentor; social support of spouse/partner and others external to a command; whether or not a member is grappling with personal issues; satisfaction with the job, superior, co-workers, or subordinates; or whether friends are staying or leaving (Jo & Ellingson, 2019). In fact, while receiving fair pay is important to turnover decisions, many studies have shown that social relation factors can weigh more strongly than extrinsic rewards (e.g., pay) when it comes to making decisions to stay or leave an organization (Kuvaas et al., 2017). In the present study we hypothesized that an analysis of both individual and community network structures would provide more nuanced insights into reenlistment decisions than can be obtained by relying solely on a traditional-based approach such as regression analysis.

SNA as an approach to retention moves beyond conventional views of turnover as an independent event based only on individual level variables. It is a tool that allows for consideration of the broader social context in which an individual is situated and the impact it may have on their workplace behavior. SNA leverages relational data about a set of actors and the ties present (or absent) among them. Actors may take a variety of forms, including individuals, groups, or organizations. Relations (aka ties), may also take a range of forms (e.g., communication, friendship, collaboration). Central to the notion of SNA is that actors are embedded in an environment, and a consideration of that environment is essential to understanding behavior. Research has demonstrated employees remain in organizations when they have strong network ties (Feeley et al., 2008; Hom & Xiao, 2011; Mossholder et al., 2005) or leave when their ties end (Felps et al., 2009).

Findings and Conclusions

This study relied on two different types of network data for a three-part study. Part A addressed the question: How are social networks related to enlisted aviation maintenance members' decision to be assigned or reassigned to NAS Lemoore? The study used focus groups and questionnaires to collect individual (ego) network data. In other words, we asked people about their important work and personal connections as well as key factors about those connections, such as whether connections were local, personal, or professional. We found that Sailors who have strong ties to their organization and community are also more likely to report having strong levels of social support, and in general reported being more satisfied with their work environment. In contrast, Sailors with low levels of connection to their work peers reported lower levels of social support, and these individuals were more likely to report a desire to leave their organization.

Part B asked: How can we leverage the Navy's archival data to understand the impact of network connections on key retention decisions? We used archival data from the DMDC database as a two-mode network (Sailor by Unit Identification Code) to create a simulated one-mode network (Sailor by Sailor) to explore how the data might be used to better understand the role of work group social connections in detailing and retention decisions. These findings suggest that social networks analysis can be used on existing data within the DMDC datasets to provide a fuller picture of who is most likely to be impacted by characteristics of their work group networks. Descriptive analysis of the networks over time were used to identify trends in work group churn, demographic distribution of Sailors within and across work groups, and retention decisions based on individuals' network position. Results of a similarity (homophily) analysis, for instance, demonstrate that in our simulated dataset, individuals were more likely to be in a workgroup with others who were making the same enlistment decisions as they were (i.e., negative homophily score suggests higher likelihood of connection to similar others than chance would suggest).

In other words, the data show hubs of re-enlistment and turnover. Further analysis of work group networks found that when gender was also taken into consideration the overall tendency to be working with others who were making the same re-enlistment decision diminished for all groups except for females who decided to leave the Navy. Social network analysis provides the Navy an opportunity to identify and explore those groups for whom connection within work groups is most critical. Resulting information can be used to inform implementation of manning practices as well as development of future human resources policies to support the Navy's goals for a diverse and properly manned workforce.

Part C asked: What specific Navy talent management functions might be able to employ SNA methods? We identified several areas where social network analysis can be applied to human resource functions throughout the MyNavy HR enterprise including recruiting, training, managing, retaining, and integrated talent management.

Recommendations for Further Research

Two different types of network data were examined in an effort to recognize both the role that traditional social networks play in sailor decision making, but also acknowledge the constraints within which Sailors make those decisions (often not having freedom to choose where they move, when they move, or who they work with). The first used qualitative methods to gather data on how individuals conceive of their individual network connections and to understand the role connections to individuals outside of the Navy play in career decisions of those within the Navy. The second portion relied on a simulated dataset using Defense Management Data Center (DMDC) data to construct work group networks.

This project identified a wide variety of areas for future research. Continued exploration into how DMDC data can be used from a network perspective is a key research opportunity. This dataset included only a small portion of the variables and cases available. Existing research suggests using a wider range of variables to shed light on structural patterns and social connections, such as religion, marital status, and hometown. Such variables would reveal ways that similarity (homophily) in work groups impact retention and other key decisions. Many of these variables are available in the larger DMDC database and could be included in future studies. The analysis of the work group networks from the DMDC data provides descriptive structural patterns, but does not identify why these patterns exist. Integrating these networks with networks of leadership, as well as command climate in different units might begin to uncover more explanatory patterns. Finally, this study did not begin the analysis of network characteristics at the individual level, which is ripe for exploration. For example, preliminary review of summary ego-network statistics at the individual level suggests a wide variation that might be wrapped into a more traditional case level analysis to understand how structural positions in a network influence viability of other retention strategies such as bonus or early promotion.

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NPS-20-N306-A: Study Return on Investment

Researcher: Dr. Johnathan Mun
Student Participation: No students participated in this research project.

Project Summary

The current research looks at various novel ways to value the monetary return on investment (ROI) of military education and research. The methodologies apply theoretical constructs by using a systems approach to utilization; convolution methods to determine the frequency and quantity of use; and an analytical framework, empirical impact analysis, and work lifecycle approach, combined with integrated risk management and knowledge value added methodologies. These combined approaches were used to determine and run Monte Carlo simulations of the model inputs, as well as to provide guidance and information to decision makers with respect to the optimal portfolio allocation of resources to educational activities. The research also includes an examination of three short case studies: one on the value of military research in the Naval Acquisitions Research Program, a second case study on the value of a naval university such as the Naval Postgraduate School (NPS) in Monterey, California, and a third case on the Defense Acquisition University (DAU), where we obtained data for 16,157 student and supervisor surveys. These ROI are above and beyond the significant intangible value of military officers studying a military-specific curriculum and learning from each other as well as from retired military faculty. Finally, we also conclude that military organizations tend to value the ROI to an employee's personal career growth as being the same as the ROI to the entire organization, where the ROI of a training initiative goes

well beyond its sole impact on an employee's job performance where the value add might be intrinsic, unmeasurable, and subjective, rather than simple applications of specific knowledge or learned skill set on the job. The results of the research will provide the Department of Defense a credible and defensible methodology and results to make better decisions and budget allocation when it comes to military education.

Keywords: *return on investment, value of military education, Monte Carlo simulation, cost benefit analysis, ROI research, value of military education, value of military research*

Background

The United States Navy and other military services send a large number of their officers to various military universities to obtain graduate degrees or perform academic research. These graduate education programs provide the officers with technical skills and nontechnical competencies highly valued in their respective billets. The cost of sending a Navy officer to a 1.5- to 2-year program for a master's degree may be upwards of $250,000 plus the opportunity cost of his or her lost services. In addition, a doctoral program may cost upwards of $500,000 per officer, plus their respective soft opportunity costs for being away for three to four years (Department of the Navy, 2018). The U.S. military's human resource environment is unique in that it is a closed internal hierarchical structure. For instance, an officer's pay is based on his or her rank and years of service, regardless of educational background. It can be argued that higher education may result in higher efficiency and productivity, thereby increasing the speed of promotions, but these are fairly difficult to quantify. Further, we see that two years after graduation, the retention rates are relatively high, ranging from 99.31% to 95.78% on average, based on our research. This high rate of retention the first few years is to be expected as officers sent to graduate programs typically are required to "pay back" their education costs with guaranteed service for several years. The question is whether the benefits of such education and research are indeed greater than the cost incurred by the Navy. Another consideration is that naval research and education are not separate tasks but tend to coexist alongside the innovation engines of the country.

The Navy's investment in education must be "fiscally disciplined focusing on the tenants of Warfighting First, Operate Forward, and Be Ready" (Department of the Navy, 2018). There is a need to align education resources with the highest priorities and return on investment. The current research examines the challenges of determining the ROI of military education. The primary objective of the research is to provide a set of recommendations and methodologies, as well as additional insights and examples of how some of these methods can be applied. The questions examined in this research are as follows:

- How can ROI be defined and calculated within the realms of military education?
- What is the ROI of military education and research?
- How can we determine the optimal allocation of resources and investments among competing initiatives in the DON, from multidomain activities to education for its officers?

Findings and Conclusions

The research looked at novel ways to value the monetary return on investment (ROI) of military education and research. The methodologies apply theoretical constructs by using a systems approach to utilization; convolution methods to determine the frequency and quantity of use; and an analytical framework, empirical impact analysis, and work lifecycle approach, combined with integrated risk management and knowledge value added methodologies. These combined approaches were used to determine and run Monte Carlo simulations of the model inputs, as well as to provide guidance and information to decision makers with respect to the optimal portfolio allocation of resources to educational activities. The research also includes an examination of three short case studies: one on the value of military research in the Naval Acquisitions Research Program, a second case study on the value of a naval university such as the Naval Postgraduate School (NPS) in Monterey, California, and a third case on the Defense Acquisition University (DAU), where we obtained data for 16,157 student and supervisor surveys.

The research findings indicate that there is a statistically significant positive impact on retention of graduating officers, lower attendance cost, and greater DoD control of the courses covered. In fact, the ROI for military-based academic research ranges between 240% and 600%, while graduate education at a military university such as NPS yields an ROI between 469% and 673%. The courses at the DAU have an average ROI between 411% and 477%, and the probability that, on average, any given course taken at the DAU has at least a 93% probability that the ROI is positive for an organization. The global average ROI for various military education is estimated to be about 485%, which means that for every $1 spent on education, the benefit gained by the government is $5.85. These ROI are above and beyond the significant intangible value of military officers studying a military-specific curriculum and learning from each other as well as from retired military faculty. Finally, we also conclude that military organizations tend to value the ROI to an employee's personal career growth as being the same as the ROI to the entire organization, where the ROI of a training initiative goes well beyond its sole impact on an employee's job performance where the value add might be intrinsic, unmeasurable, and subjective, rather than simple applications of specific knowledge or learned skill set on the job. The results of the research will provide the Department of Defense a credible and defensible methodology and results to make better decisions and budget allocation when it comes to military education.

Recommendations for Further Research

The return on investment (ROI) for military-based academic research was found to range between 240% and 600%, while graduate education at a military university such as Naval Postgraduate School (NPS) yields an ROI between 469% and 673%. The courses at the Defense Acquisition University have an average ROI between 411% and 477%. In order to facilitate the expansion and execution of the methodologies in this research, the recommendation is to apply the following research instruments, which will require institutional review board (IRB) authorization. Clearly, the efforts listed next can evolve over time based on the results obtained throughout the research project. Nonetheless, suffice to say, the effort involved going forward should be a multiyear research program. Therefore, given the time and budgetary constraints inherent in this current research, the following represents our current research's limitations and opportunities for the future.

- Better Cost Data. Higher-level precision cost data would be helpful in clearly identifying the actual ROI. The costs at NPS need to be stratified and segmented into the correct subcategories to make them comparable to private civilian universities. In addition, the cost of attrition and benefits of retention starting from the career of a junior officer through senior officer ranks need to be better quantified. Other costs would be the opportunity costs of empty billets at the senior officer and flag or general officer levels.

- Surveys. Sliding scale surveys of past graduate students at NPS and the Naval War College were used. These surveys, coupled with performance reviews, can be used to run the Analytical Framework Approach recommended in this research.
- Focus Groups. Qualitative and intangible value to society, service, and the nation can be culled from such focus group discussions. Anecdotal evidence can be obtained and extrapolated to incorporate other pockets of evidence of intangible value of military education and research.
- Follow-up Questionnaires. These can be numerical in nature and are based on the responses from the initial surveys and focus group results. The questionnaire can also be used to follow up on previously determined anecdotal events.
- On-the-job Observations. These observations can be performed if a certain learned skill or applied research is put into action. The number of times a certain skill is triggered is noted. The information captured can then be fed into the Knowledge Value Added methodology and Monte Carlo simulated to determine the potential impact on cost reduction and efficiency increase in having the research or knowledge applied.
- Performance Reviews. Multiple year performance review of graduates before and after their education program, as well as a random selection of performance reviews of other officers with similar billets and rank, which can be used as a control group. Using these hard data, meta-analysis can be performed, and both the Empirical Impact Approach and Analytical Framework Approach can be applied. This is similar to a controlled test when comparing before- and after-effects and with-without effects of education and research.
- Tracking Over Time. The graduates' career should be tracked over time, including promotions and billet changes.

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NPS-20-N319-A: Blended Training Environment

Researchers: Dr. Simona Tick, Dr. Jennifer Heissel, Dr. Kathryn Aten, and Dr. Judith Hermis
Student Participation: LT Roy Bliss USN

Project Summary

In this study, we examined current state-of-the-art personalization of distributed learning, as well as the evidence on the efficacy of adaptive and personalized training and education. Based on our findings, we developed a typology of training objectives matched to effective instructional design features. Next, we applied the typology to identify feasible alternatives to the current instructional design and delivery for technical Navy training programs. We then conducted an evaluation of the advantages and trade-offs of adopting a blended training environment for technical Navy training, when compared with traditional classroom training, taking into consideration the level needed to achieve the training requirements, the experience of the trainees, and the resources used. Based on our findings, we developed an Instructional System Design (ISD) transition roadmap with recommendations for on-site assessment of blended training efficacy, acquisition, and implementation, which can facilitate the integration of Navy training

into the future learning continuum concept.

Keywords: *Navy blended training, instructional system design, ISD, learning continuum*

Background

In recent years, the Navy has increased its efforts to improve assessment of training quality and impact on fleet readiness. Earlier evidence suggests that incorporating greater personalization into distributed learning could achieve significant gains in learning effectiveness. To preface their case study on blended training for U.S. Army leader training, Straus et al. (2013) describe a few examples of effective blended learning, noting that instructional design is key to effective learning, as opposed to the learning venue. Current Navy approaches to ISD do not adequately address the development of personalization and adaptive training techniques. Adopting a blended training environment, such as combining online materials and opportunities for interaction with traditional classroom methods, could offer a solution to improving the assessment of training quality and impact on fleet readiness, and support the integration of Navy training into the learning continuum envisioned for the future.

The goal of this study was to identify the pros and cons of a blended training environment in the context of specific Navy ratings training. From there, we worked to develop a roadmap for the transition to an ISD which aligns with the capabilities of a blended training environment, which would in turn, leverage pervasive learning techniques and optimize delivery to individual students.

Findings and Conclusions

Emerging technologies have pushed the landscape of education and training to incorporate a full spectrum of content organization, delivery, and assessment modes, from traditional face-to-face, same-content-for-all formats to online, personalized, and continuous learning, which can leave a persistent impact on the learner's career. In this study, we reviewed the state-of-the-art in personalization of distributed learning and effective blending of content delivery approaches. Further, by reviewing prior studies and published reports from the private sector, academia, and the military, we examined the evidence on the efficacy of adaptive and personalized training and education. In addition, we conducted a review of past Navy distributed learning experiences to identify any lessons learned. Based on the identified advantages and tradeoffs associated with different ISDs in meeting training and educational outcomes, we developed a typology of training objectives, which matched with effective and efficient instructional design features. This allowed us to then identify feasible blended training alternatives to current technical Navy training to facilitate the integration of Navy training into the future learning continuum concept. Further, using a cost-benefit analysis framework, we analyzed the pros and cons associated with meeting learning outcomes and resource use for blended training alternatives as compared with the current traditional training modality.

Based on the findings from of our analysis, we developed a transition roadmap tailored to the learning requirements of technical ratings. Additionally, we developed recommendations for acquisition, implementation, and assessment for an instructional system design that is better aligned with the capabilities of a blended training environment.

Recommendations for Further Research

The Navy is increasingly focused on improving assessment of training quality and impact on fleet readiness. Blended training can offer a balanced solution, by meeting the needs to facilitate the integration of Navy training into the future learning continuum concept. However, future studies are needed to conduct on-site assessments of the efficacy of blended training in terms of meeting training objectives, on the resources used, and on the potential impact of fleet readiness. Further, given the Navy's large array of training programs, the assessment of blended training alternatives will have to be tailored to the different learning requirements of touch labor-, administrative- and information technology-focused ratings.

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NPS-20-N326-A: Reliable Learning without Persistent Network Access

Researcher: Dr. Randy Maule
Student Participation: Maj Jorge Caro USMC

Project Summary

In this research, we examined architecture design variables, including naval service architecture, the Total Learning Architecture, micro-service architecture, hybrid cloud architecture, and cybersecurity for distance learning. Results are presented in decision frameworks for distance learning architecture designers and administrators.

Keywords: *distance learning, training, learning management systems, LMS, Total Learning Architecture, TLA*

Background

The Naval Science & Technology Strategic Plan "Warfighter Performance" objective addresses: (a) Training technologies to enhance fundamental information-processing abilities in young adults; (b) Techniques to shorten training time, reduce training costs, and maximize training impact; and (c) Tools and techniques to achieve ubiquitous, engaging, scenario-based training (Office of Naval Research, 2011). We reviewed the Total Learning Architecture (Advanced Distributed Learning, 2020) and legacy Learning Management System initiatives in this research, addressing software variables for always-on, on-demand training and education.

Findings and Conclusions

This project presented architecture options, software components, and deployment options for next-generation ship distance learning architecture, including DoD and fleet cybersecurity processes. Technical analysis included options for distributed data storage, offline operations, record synchronization, and deployment infrastructure.

Recommendations for Further Research

Recommended next steps would be to re-engineer key software components to enhance cybersecurity and re-code select components to better address supply chain maintenance.

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NPS-20-N333-A: Inference on Missing Information on a Social Network

Researcher: Dr. Ruriko Yoshida
Student Participation: LT Ross Spinelli USN

Project Summary

Machine learning (ML) methods have become a popular compliment to traditional network analysis techniques. This is particularly true when the challenge of uncertainty enters the picture but can be overcome with the application of ML methods with large amounts of data. Understanding a social network between workers can be used for modeling social relationship factorial analysis to improve connectedness of Sailors and reduce destructive behaviors, including connectedness of all Sailors, and reducing many destructive behaviors in N17, such as alcohol/drug use, suicide, and others, in addition to sexual harassment and assault. In order to analyze as accurately as possible, it is important to have an accurate social network and that the observed social network is built with complete information. However, in reality an observed social network is very often built with missing information.

We proposed here to infer connectedness of the social networks in a community within the Navy from a data set with missing information. After correctly selecting a model to infer missing parts of the social network, we analyzed strength of relationships between workers. In this social network, we set workers in a group as nodes, and we drew edges between nodes if they have some social interaction between them. By this way, we could construct several social networks, like communication networks.

In this research, our computational experiments with simulated and empirical data sets show our methods perform well to infer network statistics with missing information. We recommend the following next steps: Obtain the Alcohol Drug Management Information Tracking System (ADMITS) and Defense Equal Opportunity Organizational Climate Survey (DEOCS) data sets from OPNAV N17 and apply our reported methods to analyze belonging social support and how it affects stress among Sailors using the social network analysis.

Keywords: *network completion problem, social networks, machine learning*

Background
Scientific research indicates that relationship factors, such as connectedness, toughness, and trust, are associated with choices that promote desirable signature behaviors or reduce destructive behaviors. Through the Culture of Excellence approach, the Navy is shifting behavioral research and programmatic efforts for reducing destructive behaviors away from siloed initiatives to a more holistic approach. This approach focuses on achieving warfighting excellence by fostering mental, physical, and emotional toughness, promoting trust, and ensuring connectedness for all personnel throughout their Navy journey.

A priority for OPNAV N17, the 21st Century Sailor Office, is identifying destructive behaviors among Sailors in a command unit, ranging from suicide to sexual assault. We are working closely with OPNAV N17 to establish a method to identify at-risk personnel prior to any incidents. Command climate surveys are used in every command, but analyzing this data with current methods can be slow and time-consuming. We propose using predictive network analysis to identify at-risk individuals in a network based on their relationships to others.

Suicide and sexual assault continue to be two major concerns in the military. While there are several indicators to identify if a person is suicidal, there are not as many indicators or psychological tests that can be performed to identify someone as a potential sexual victimizer. We believe predictive network analysis, combined with historical data, can be used to identify a potential sexual abuser in a unit prior to any negative actions occurring. This research establishes the base model to identify an individual in a command unit network based on bonds or relationships among people.

To analyze social networks among people of interest, using ML techniques and network analysis studies can be powerful. From these ML techniques, a unique pattern of relationships among people in military units can be established, and we can create algorithms to help identify links among individuals in a command unit. These links help form the basis for identifying how closely connected people are related. For example, using metadata, such as the frequency of calls people made and whom they called, we can predict relationships, such as their partners, friends, and coworkers.

Links, or relationships, among people are not always reported, which leads to many problems when working with a social network. In social networks particularly, people may lie about their relationships to others or just not recall certain facts during the survey that establishes links between two people. The amount of information not provided or missing from a network is not known in advance.

Unfortunately, very little research has been completed to study the effects of incomplete data on network structures. Most techniques for handling incomplete networks involve data imputation, the process of estimating unknown data from the observed data, which might lead a wrong conclusion and ultimately affect classification.

In this research, we developed novel methods written in RStudio to conduct social network analysis with missing information and the results were reported in a thesis by LT Ross Spinelli and a paper written by the PI and LT Vu.

Findings and Conclusions

If we have missing information in an observed social network, the result from analysis on the network might be misleading. For example, if a victim of sexual harassment or work harassment never reports their relations with their attackers, the consequence of a network analysis with missing information can be significant. Therefore, we propose to develop statistical and machine learning methods to fill the gap.

In this research, we propose a novel non-parametric method to predict connections between two people in the social network based on personal information, such as alcohol use, working hours, etc. With our ML method we might be able to predict "hidden" or "missing" connections among people in a social network. Our method consists of two stages: First we determine the percentage of information missing, allowing us to completely rebuild the network structure with all information about relationships in the unit. These relationships have a direct connection to identifying a person with a likely destructive behavior. Then we apply random forests (RFs) to predict the connections between people (edges of the social network). The goal of the second step is to predict edges in the graph from personal information/attributes using the RF model. This allows us to estimate the relationships among the nodes that were previously missing or not reported.

Our results strongly indicate the need to include incomplete network representations in training the classification model. Incorporating incomplete networks at various stages of completeness allows the machine to examine and learn the nuances of incomplete networks. By allowing the machine to study incomplete network structural features, it has an improved ability to recognize and classify other incomplete networks. The RF classification model requires minimal computational effort and can accomplish an efficient classification. We confirmed these simple, easily calculated network features are sufficient to classify an incomplete network.

We also applied our method to a dataset based on friendships among primary school females in West Scotland. This dataset creates edges by linking two people if they say they are friends. From this, we examined personal attributes and tried to correlate which attribute factors aid in the development of friendships among peers on the network. Accuracy rates showed that our method works well with this dataset.

We are currently working closely with OPNAV N17, the 21st Century Sailor Office, to identify members in a command unit. As a future line of research, by identifying relationships and the connecting attributes, we may be able to apply our method to identify a potential destructive behavior, such as harassment, DUI, and usage of illegal drags. We can use this information to help rebuild networks with missing data based on these known attributes.

Recommendations for Further Research

Innovative efforts are underway within the Navy to encourage communication and connectedness. Scientific research indicates that perceptions of connectedness (i.e., social support) can help buffer against adverse reactions to stress and that social integration has positive effects on wellbeing. Yet for the Navy to most effectively enhance connectedness among Sailors, research is needed to understand the characteristics of professional/social networks that lead to a greater social integration in the Navy and to understand the manner in which these characteristics relate to perceived interpersonal connectedness and support for Sailors.

Social connectedness affects stress in many ways: as Holt-Lunstad et al. (2010) hypothesized, it affects health and wellbeing positively, but our initial study shows that it might also affect us in negative ways, for example, increasing destructive behaviors such as illegal drug use and abusive behaviors. In June 2020, we finally obtained the Alcohol Drug Management Information Tracking System (ADMITS) data set obtained from OPNAV N17. From here, we recommend to study the relations between connectedness, the effects of stress, and destructive behaviors among Sailors using our developed methods in this study. First, we will infer connectedness of the social networks in a community of Sailors. After correctly selecting a model to infer, we will analyze strength of relationships between them. By this method we can construct several social networks, like communication networks. Then based on the social network we reconstruct, we will conduct logistic regressions to see which factors contribute to each relationship. Next, we will conduct statistical analysis to infer correlations between connectedness, the destructive behaviors, and the effects of stress. Finally, we will apply our models to the ADMITS data set as well as the Defense Equal Opportunity Organizational Climate Survey (DEOCS) data set obtained from OPNAV N17.

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NPS-20-N338-A: The Effects of Minority/Female Role Models and Diversity on Retention

Researchers: Dr. Jeremy Arkes and Dr. Simona Tick
Student Participation: LT Cesar Serna USN, LT Jesse Hernandez-Rodriguez USN, LT Jeremy Thomas USN, and LCDR Capreece Dunklin USN

Project Summary

This study uses a sample of Navy personnel data for personnel entering the Navy between FY1995 and FY2012 to examine how higher levels of diversity among peers and role models affect retention. To test for this effect, we estimated fixed-effects models that regressed the first-term retention decision on the proportions of shipmates who were Black, Hispanic, and female. We found some cases of strong evidence that greater diversity positively affects retention for both underrepresented groups, as well as majority groups. In an accompanying qualitative analysis from interviews with first-term Sailors on Navy ships, we learned that members of underrepresented groups, compared to others, tend to face greater obstacles resulting from institutional Navy rules, tend to have inferior experiences with mentors, have more communication challenges with peers and superiors, and feel like they have fewer opportunities in the Navy. Greater diversity among peers and superiors might be able to address some of these more challenging experiences.

Keywords: *Navy inclusion and diversity, underrepresented groups, retention, prior-enlisted*

Background

In recent years, inclusion and diversity have become a major priority for the Navy. In the Navy, members of underrepresented racial/ethnic groups tend to have high representation (relative to their population representation) among enlisted lower-ranked personnel, but low representation among officers and higher ranks for both enlisted Sailors and officers. Likewise, females tend to have lower representation among more senior ranks and experience levels, compared to their representation at entry. This project aimed to better understand how greater diversity could impact retention in the Navy, particularly for members of underrepresented groups. Diversity is measured as the percentage of Sailors from underrepresented groups (Blacks, Hispanics, and females) among the crew of the sailor's ship, as measured at the end of each quarter.

Findings and Conclusions

A qualitative analysis was included in this study that involved visits to four ships and used: (1) surveys on the importance of, and experiences, regarding 20 retention factors (drawn from Maslow's Hierarchy of Needs); and (2) semi-structured personal interviews to better understand these factors, and particularly factors related to diversity. Unfortunately, despite having a high response rate, the surveys did not have enough observations for different racial/ethnic groups and females to draw robust inferences on differences within these groups. Therefore, the interviews provided the greatest value from the qualitative analysis. The main themes that came from the interviews were the following: 1). Underrepresented groups appear to face greater obstacles linked to Navy policies, culture, and interpersonal communication than the majority groups. 2). Underrepresented group members have inferior experiences with mentors. 3). Underrepresented group members tend to believe there are limited opportunities for them in the Navy. 4). Underrepresented group members are more likely to mention difficulties fitting in with peers. 5). Most junior personnel prefer working under prior-enlisted officers.

Our primary analysis was a quantitative analysis of the effect of diversity of ship crews on retention. In particular, we estimated how more Sailors of underrepresented groups (particularly Blacks, Hispanics, and females) on a sailor's first ship assignment affected the likelihood of reenlistment for first-term enlistees or retention for junior officers. The retention analysis was conducted for both the members of the underrepresented groups and for the majority groups' (Whites and males) shipmates. The shipmates were separated by officers vs. enlisted in one set of models and peers vs. superiors (within the enlisted or officer ranks). We aimed to examine how greater diversity affected retention, not just for underrepresented groups, but also for the majority groups. The separate samples of enlisted Sailors and officers included all who entered the Navy between October 1994 and June 2012 (to give them time to make a retention decision) and who had at least five end-of-quarter observations serving on the same small- or medium-sized ship. We excluded aircraft carriers and amphibious assault ships because they are so large that it is unlikely a given sailor would know everyone on the ship—thus, the diversity of the whole ship would be less meaningful.

The main results for enlisted Sailors were the following: 1). Black Sailors' retention likelihood is positively impacted by a higher percentage of Blacks among the enlisted crew, with a stronger effect apparently coming from more Blacks among enlisted superiors rather than enlisted peers. 2). There is some evidence that White enlisted Sailors' retention is positively affected by having more Black peers or more Black officers. 3). There are no detected positive effects of more Hispanics (among officers or enlisted) on the retention rates of Hispanics, which could be due to the different sub-groups within Hispanics. In contrast, White and Black Sailors appear to be more likely to reenlist if they have more Hispanics among enlisted superiors. 4). There is no evidence that females' retention rates are positively affected by having more females in the crew or any segment of the crew. However, males' retention is significantly positively affected by more females among the officers and among enlisted peers.

One other interesting result is that serving with more officers who are prior-enlisted has large positive effects on first-term retention.

The results from officers proved not to have enough power to generate estimates that were precise enough to detect any effects; even quite large effects would not have established statistically significant findings.

Part of our original objectives were to examine the same effects for large ships, looking within those in the same rating or designator code on a given ship to identify the peers. However, the results were imprecise, and nothing was significant; this is likely due to mis-identifying the sailor's true peers on the larger ships.

Recommendations for Further Research

We formulated several recommendations for the Navy based on our quantitative results and a few themes from the interviews in the qualitative analysis. However, they must be qualified as our understanding of the true mechanisms behind why retention for enlisted personnel tends to be higher for those serving under more officers and enlisted leaders from underrepresented groups is partially speculative and partially based on educated guesses from the interviews. Therefore, our recommendations presume that all major mechanisms we mentioned above (a mentoring effect, a role-model effect, and contributing to a healthier command environment) are at play. Our recommendations are as follows: 1). gain a better understanding of the challenges faced by underrepresented groups; 2). continue to expand efforts to make the whole fleet aware of unconscious biases; 3). explore whether increasing the number of enlisted Sailors who can enter commissioning programs would be cost-effective, taking into account the increased enlisted retention resulting from having more prior-enlisted officers; 4). gain a better understanding of the characteristics and leadership qualities of prior-enlisted officers, which that make them preferred officers to work with; and 5). increase efforts to ensure underrepresented-group Sailors are receiving adequate mentoring from relevant superiors. All of the above have the potential for increasing retention among the most talented of the underrepresented groups and, ultimately, increase representation of these groups in leadership positions.

NPS-20-N351-A: Embedding a Formal Knowledge Management (KM) Process

Researchers: Dr. Shelley Gallup and Dr. Mark Nissen
Student Participation: LCDR Felicia Godfrey USNR and LT Eric Barkley USN

Project Summary

Building upon initial efforts to engage with industry and conceptualize a Navy KM strategy, the research described in this study employs a combination of Congruence Model analysis, Knowledge Flow Theory, and qualitative methods to outline an approach for developing a formal Navy KM process. This work involves surveying best tools and practices in the industry, government and nonprofit sectors, augmented by in depth field research to examine two specific Navy organizations in detail. Results are highly promising, and they serve to illuminate a path toward improving Navy knowledge flows as well as continued research along these lines.

Starting first with Navy recruiting organizations that are "transitioned" and "legacy," the study looked at the processes and knowledge flows required for successfully meeting personnel acquisition objectives. Recruiting is rich with knowledge passed from recruiter to recruiter (tacit) and also has to work within the formal organization of the Navy Recruiting Command. Using tools such as the Congruence Model for organization performance and fit, knowledge flows involving tacit and explicit knowledge, and combining the two models to understand what knowledge prescriptions are needed across segments of the organization, the study was able to construct a detailed understanding of knowledge and organization dynamics. Concurrently, industry knowledge management systems were reviewed and differences with Navy needs better understood.

Keywords: *knowledge management, Embedded Knowledge Process, knowledge flows, Congruence Model, process and organization design*

Background

High power knowledge does not just appear automatically when and where it's needed. Rather, an organization must possess the capabilities and processes required: a) to amplify knowledge to high power levels, and b) for such powerful knowledge to flow—rapidly, reliably and energetically—from when and where it is to when and where it needs to be. Like land, labor, capital and technology, knowledge needs to be managed, hence the popular term knowledge management (KM). This represents a fundamental KM principle (Nissen, 2006).

The Navy N1 (Personnel) organization has yet to develop a formal process for KM. This puts the Navy in a position of competitive disadvantage, especially as thousands of naval personnel change jobs every day, often taking their hard-earned job knowledge out the door with them and leaving their replacements with the need to learn the same knowledge anew.

Findings and Conclusions

The research confirmed that tacit knowledge, while "slower" than explicit knowledge is still the most effective way for new recruiters to capitalize on the learning of experienced recruiters. This was an expected result; however, there are needs for explicit knowledge within the organization as well. In addition, as knowledge tools are added to the organization, there is a need to re-adapt to the change. Organization change, technology, and knowledge flows all must "fit." Vendor solutions were researched for applicability. In general, they fit into two categories, of indexing all information to be extracted by query or using semantic logic that associates words to create useful information from across the knowledge eco-system. Another project with the Navy Special Operations Command is considering both, and these authors are working with surrogate data from the Naval Safety Center to test both approaches. Non-government solutions in general are complex, expensive and not a direct fit to Navy needs.

Recommendations for Further Research

One important contribution centers on a set of pathologies currently afflicting the Navy recruiting process, along with a set of recommendations for addressing such pathologies and improving the process. Another important contribution revolves around the inherent generalizability of our approach and results: other Navy organizations and processes (i.e., beyond recruiting) offer excellent potential for analysis and recommendations along these lines. A third important contribution involves an improved understanding of how to embed KM into a Navy organization: leaders must do more than simply try to overlay KM onto existing processes and structures. A fourth important contribution highlights our ability to adapt the Congruence Model to incorporate knowledge flows as a novel element of organization fit.

N2/N6 - Information Warfare

NPS-19-N324-B: Mission Architecture for Maritime Domain Awareness Using Small Satellites

Researchers: Dr. Wenschel Lan and CDR Charles Racoosin USN

Student Participation: LCDR Jessica Alexander USN, Maj Jonathon Bouska USMC, LCDR Evan Bower USN, LT Harrison English USN, LT Rachel Hill USN, LT Raymond Lanphere USN, LT Samuel Nichols USN, Maj Kelly Raisch USMC, Capt Sean Rynning USMC, Maj Dane Sagerholm USMC, LT Julian Sevillaparra USN, Capt Morgan Trent USMC, Capt Samuel Wood USAF, and LT Kenneth Wooten, USN

Project Summary

This research is a follow-on effort, focusing on the utility of a synthetic aperture radar (SAR) sensor payload for the Maritime Domain Awareness (MDA) mission instead of the use of an electro-optical (EO) sensor. Just as with EO sensor payloads, numerous commercial SAR constellations are already on orbit, or are expected to be fielded soon. However, none of these meet the challenging requirements of the MDA mission in support of US Navy (USN) objectives.

A technology forecast showed that a SAR payload could provide a considerable advantage over both an EO sensor and an IR sensor. Our research concluded that a SAR sensor does overcome the night- and weather-related limitations of the EO sensor, and there were improvements in search capability, but the power required for a SAR sensor limits the orbit to low-earth orbit (LEO). The required revisit time is very short, requiring hundreds of satellites—currently, a very costly manufacture and launch proposition. The spacecraft would also need to be dedicated to the MDA mission, which may pose a problem for the littorals, for which there would likely be competing terrestrial and maritime requirements.

It is recommended that the Navy continue to analyze and pursue a space-based MDA capability as rapid advances in the commercial space sector may provide near term solutions to the MDA mission. SpaceX's Starlink has already demonstrated the ability to manufacture and launch a constellation of over 600 satellites in a mere five years, which are connected through a high capacity, cross-linked communication architecture that can satisfy the command and control (C2) necessary for sensor tasking and data retrieval from the SAR sensors.

Keywords: *maritime domain awareness, geospatial intelligence, GEOINT, small satellites, constellations, synthetic aperture radar, SAR*

Background

Our previous research (Newman, 2018; Begley, 2018; Crawford, 2018; Mcgowan, 2018) investigated the feasibility of a small satellite (SmallSat) constellation to increase intelligence, surveillance, and reconnaissance (ISR) in support of MDA. While commercial SmallSat companies such as Planet Labs, BlackSky, Adcole Maryland Aerospace, and UrTheCast demonstrate feasibility of an EO small satellite (SmallSat) constellation, none of these companies' spacecraft are in constellations that provide the necessary revisit for MDA, which is typically less than 30 minutes.

At the time of our previous work, no commercial satellite architecture was available for leverage, therefore a purposed-built constellation of 180 EO small satellites was recommended. After taking into consideration the currently available technology, cost, the number of satellites per launch, and launch tempo, the Falcon 9 is the recommended platform to deploy this constellation. Potentially, the entire constellation could be placed into orbit via six launches over the span of two to three months, costing roughly $372M. Our recommended course of action was to invest further research in command, control, and communications; payload sensor; and processing. We also recommended further investigation into the optimization of the constellation and launch pattern, as well as the development of smaller launch vehicles with rapid launch tempo capabilities.

In our current research, we focused on the payload sensor type. The EO sensor restricts imaging to daylight hours, but we recommend researching the potential use of other sensor types such as infrared (IR) or SAR for increased imaging opportunity and timeliness. An initial trade study and technology forecast showed that a SAR payload would provide a considerable advantage over both an EO sensor and an IR sensor.

The use of a SAR sensor has the potential to overcome night- and weather-related limitations of the EO sensor, and the larger potential instantaneous field of view (FOV) and sensor field of regard (FOR) can improve the search ability above what the EO sensor could provide. However, due to power limitations, the altitude at which SAR satellites can be deployed (LEO) limits the sensor FOR, and the very short revisit time requirement drives constellations numbered in the hundreds of satellites at LEO. Additionally, power limits the duty cycle of the payload, and dictates that the sensor be dedicated to the MDA mission. For open ocean regions, this may not be an issue, but for the littorals, there would likely be competing terrestrial and maritime requirements for its use.

Although numerous commercial SAR constellations such as Capella, PredaSAR, Iceye, and XpressSAR may individually advertise the ability to observe a point on the surface of the Earth several times each day, none could provide the very short revisit time necessary to provide targeting quality knowledge of potential target location in real time. Even when combined into a much larger "virtual" constellation, since these separate constellations were not deployed in a coordinated scheme, the combined performance was little improved over their individual capabilities.

Findings and Conclusions

The architecture design process was used to assess the utility of a SAR payload for the MDA mission. This determining the desired objectives and defining constraints, performing a technology forecast and developing evaluation criteria, developing and evaluating alternative architectures, and iterating this process to arrive at the proposed design for implementation. We found that a modern, space-based SAR sensor can provide the required ~1.0 m spatial resolution for target identification. However, this is typically achieved in radar modes with smaller FOVs less suited to search. The trade-off that SAR offers over an EO sensor is that SAR systems offer other modes of operation which achieve larger FOVs—consistent with search—in exchange for lower resolution. This aspect imposes both additional constraints and opportunities on a space-based SAR architecture. If there are no potential targets in the sensor FOV (when operating in a search/low resolution mode), the sensor can cover a large area. If a potential target is detected with the search area, and this detection is autonomously recognized on board the satellite, the satellite may shift into a higher resolution mode for target recognition and identification (provided the target will remain in view of the moving satellite for an appropriate amount of time). If the satellite will not be in view of the target for a sufficient time, and the target's location can be communicated to the next satellite expected to have the target within its FOR, the following satellite can complete the target identification process.

Therefore, a mature automated target recognition capability hosted on board the satellites, tied together through an integrated, high-capacity C2 system will enable the SAR sensors to exploit both their search and identification capabilities. A modern EO sensor, such as on WorldView-4, with a resolution of ~0.3 m from ~600 km altitude, could be put at an altitude three times the original to increase the sensor FOR and still retain the desired ~1.0 m resolution. However, this sensor is still constrained by night and weather, and given its very small FOV, is not suited for search. In turn, a SAR sensor overcomes the night, weather, and FOV limitations, but since the satellite is active and must generate the radio frequency (RF) power for the two-way "round trip" of a radar pulse, each doubling of satellite altitude requires an increase in power of sixteen-fold—a calculus which quickly limits the practical altitudes for such a sensor to LEO. The physical size and mass of a SAR satellite will also be impacted—either by the satellite altitude or the desired duty cycle, or both. This, in turn, will also be a driver for the number of satellites that can be launched on a single booster—both of which will be drivers for the cost to build and launch such a constellation.

Recommendations for Further Research

It is impractical to expect purely human analysis of the data collected by many hundreds of synthetic aperture radar (SAR) sensors—clearly, some sort of automated capability is required. Increasingly, the commercial world is looking at similar problems: the self-driving car being the most obvious example. As with satellite manufacturing and launch, the maritime domain awareness (MDA) solution may come from these efforts. The ability to recognize a potential target within the SAR field of view and analyze its features for identification purposes (friend or foe? hostile or non-hostile? threat or non-threat?) may actually be more straightforward than the requirements levied on the more cluttered scene observed by a car's sensors.

It is recommended that the Navy continue to analyze and pursue a space-based MDA capability as rapid advances in the commercial space sector may provide near term solutions to the MDA mission. SpaceX's Starlink has already demonstrated the ability to manufacture and launch over 800 satellites into the low-earth orbit (LEO) regime in a reasonably short period of time; and, the Starlink constellation also possesses a high capacity, cross-linked communication architecture which would satisfy the command and control (C2) necessary for sensor tasking and data retrieval from the SAR sensors. Or, if C2 is not provided as a service, the cross-link technology could be incorporated into the sensor satellites to provide their own communication network.

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NPS-20-J315-A: Integrating Joint Fires in Support of DMO with Focus on Integrating Unmanned and Conventional Fires

Researchers: Dr. Eugene Paulo, CAPT Scot Miller USN Ret., Dr. Paul Beery, and Dr. Wayne Porter CAPT USN Ret.

Student Participation: Maj Kelly Haycock USMC, Lance Kerestes CIV, Brenda Menees CIV, and Axel Rodriguez-Negron CIV

Project Summary

This research addresses two topics: the first topic (NPS-20-N315), examines the combination of an improved cooperative engagement capability (CEC) and command and control (C2) for an adaptive force package (AFP) operating within a simulated Distributed Maritime Operations (DMO) environment. This research examines four important entities of the CEC. First, a CEC has an observer capable of identifying the precise location of a potential target. In the missile threat environment, the precision of location detail must be extremely high and updated often. This functional element is the "observer" or sensor function. Second, a complete CEC has the capability to exchange this high-fidelity, target-quality data from the "observer" platform to other participating platforms. Third, a complete CEC has a firing platform with a munition capable of successfully prosecuting the observed target. Fourth, a complete CEC has a decision support/decision making capability where the human decision-maker interfaces with the system and expresses his or her weapons release authority. The combination of the observer, decision maker, and shooter is referred to throughout this report as the "lethal triad."

The simulation centers on the mission of a friendly Blue Force (BF) controlling the enemy Red Force's (RF) influence on a strategic, bottleneck, trade route and the execution of the kill chain functions performed by the BF during the conflict that ensues. There are multiple messages exchanged between the lethal triad during execution of the kill chain functions and a recognized need to increase the C2 responsiveness while performing CEC to ensure overmatch of a near peer enemy. Of utmost importance are the effects that shortening the C2 cycle should have on the kill chain and the outcome of a battle. The kill chain benefits should include faster, less jammable communication between the lethal triad, more responsive, reliable decision making in a highly contested environment, and improved matching of weapon systems to threats.

Study results indicate that by improving interoperability and human decision making, lives are saved because fewer BF platforms are lost and overmatch against a near peer enemy is maintained. Results show that the most significant factor the Joint Fires (JF) are facing is the mismatch between human cognitive response time and the enemy engagement speed. Human decision makers introduce delays into the C2 system that could hinder the ability of the JF to promptly react and defend their platforms in future conflicts. JFs should consider pursuing artificial intelligence and machine learning algorithms to greatly reduce the C2 cycle times and data exchange delays.

For the second topic (NPS-20-N238), our research determined that JF in support of DMO is doctrinally supported and stops there. Researchers explored data strategies, modeling, cognitive assistants, innovation practices, and human machine teaming. An aggressive enterprise approach, coupled with a well-executed data strategy and a reimagining of the C2 approach, plus a focus on technical approaches that reduce the Observe Orient Decide Act (OODA) loop, were essential. We recommend that modeling techniques, such as those so expertly employed in the rest of this study, be continued.

Keywords: *Joint Fires, JF, cooperative engagement capability, CEC, distributed maritime operations, DMO*

Background

For the first topic, significant recent research that impacts JFs provides a foundational theory of fast C2 in a complex and dynamic environment. This previous research centers on the 2019 dissertation entitled, "Summary of a Framework for Engineered Complex, Adaptive (CA) System of Systems (SoS)" (Johnson, 2019). Of particular interest for Joint Fires in DMO, this research illustrated the value of engineering complex adaptive combat systems of systems capable of displaying emergent behavior to outpace the enemy decision cycle by networking friendly force platforms with embedded intelligent agents and decision makers in a way that makes rapid self-organization, distributed decision making, and cooperative engagement possible. This research applies Johnson's findings to answer the following two questions: 1) What are the requirements for an engineered C2 system that can interconnect friendly force platforms and decision makers in a way that makes rapid self-organization, distributed decision making, and cooperative engagement possible? and, 2) Can the inclusion of joint manned and unmanned platforms in the scenario space further improve the results?

The current Navy C2 capabilities must be capable of supporting an advanced CEC that supports interoperability of modern combat platforms like the F-35 and the Aegis. Distributed operations depend upon robust and timely C2 to exercise an effective CEC. There is an urgent need to develop a systems architecture that standardizes and speeds C2 interoperability to improve the overall joint force effectiveness in air and missile defense, naval surface, and air strike warfare by bringing platforms together in a joint CEC (JCEC). The focal point of this research is to understand the increased effectiveness of the kill chain by implementing shorter C2 cycles between 1) the observer conducting intelligence, surveillance, and reconnaissance (ISR); 2) the shooter; and 3) a more empowered, forward weapons release authority also known as the decision maker (DM). This will depend upon improved CEC interoperability and implementation of a CEC mesh network. Of utmost importance are the effects that shortening the C2 cycle should have on the outcome of a battle. The kill chain benefits should include faster, less jammable communication between the lethal triad; more responsive, reliable decision making in a highly contested environment; and improved matching of weapon systems to threats.

For the second topic, prior research uncovered DMO characteristics and JF practices. This research leveraged the findings of this capstone project, with other research into the Marines' fire support coordination cognitive agent concept and the Navy operational data strategy, to develop a possible way forward for JF in support of DMO. To increase the possibility of success, innovation practices were studied as well. The researchers leveraged their own ongoing research on how humans ought to interact with Maritime Strike planning agents.

Findings and Conclusions

For topic one, proposed lethal triad interoperability improvements for shortening current C2 cycles during the kill chain execution include digitization of typically analog messages relayed between the lethal triad, radio messaging translation from one protocol to another, automation of the best solution for the lethal triad, and incorporation of Multifunction Advanced Data Link (MADL) communications similar to that used on the F-35. The implementation of these improvements on every platform should allow for the creation of a distributed C2 network.

Capability and functional models of the proposed improvements have been developed along with a simulation of the mission scenario using various combinations of the BF lethal triads attacking and defending against the enemy RF weapon systems with realistic weapon system parameters incorporated including unmanned. The simulation data collection and analysis results indicate a 5.9 % to 6.4% increase in survivability of the BF while implementing the proposed JCEC C2 interoperability improvements with the greatest improvements due to automated decision making. Additional data also indicates that accelerating the kill chain via JCEC C2 improvements allows for as many as 12 additional BF munitions to become available for fire and for 4.6 additional RF munitions to be destroyed, thus acting as a form of BF multiplier. BF losses are also reduced by 12.6%.

These results indicate that by improving interoperability among the lethal triad and by improving human decision making through automation, warfighter lives can be saved because fewer BF platforms are lost and overmatch against a near peer enemy in 2030 is maintained. The analysis supports that the single most significant factor the JF is facing is the mismatch between human cognitive response time and the speed at which future enemy hyper velocity projectiles (HVPs) may travel. The data indicates that human decision makers introduce significant delays into the C2 system that could hinder the ability of the JF to promptly react and defend their platforms in future conflicts. The JFs of 2030 should consider pursuing artificial intelligence and machine learning algorithms to greatly reduce the C2 cycle times and data exchange delays of the JCEC C2, thereby increasing the chances of neutralizing newly developed and faster incoming threats.

For project topic two, four elements were central to succeeding with JF in support of DMO:
Develop a Joint Fires enterprise approach; however, this does not mean a toothless working group where work is performed as a collateral duty, but rather an empowered, Flag-led group, fully focused on delivering JF ISO DMO. They converge to joint solutions and influence service investment. One group task is executing a JF ISO DMO data strategy, based on the broader Navy operational data strategies. The second group task is exploring the C2 options for JF ISO DMO. The current clunky approach for JF may only suffer only small technical challenges and be salvageable. Now is the time to explore all options: centralized; decentralized; and emission control approaches. We sense that the correct answer is an adaptive combination of all, supported by better tools. Accelerate the JF in support of DMO OODA loop. Identify slow spots and develop options for fixing. Consider using smart agents and user proxies for both planning and execution. Use human machine teaming technologies and use Human Machine Teams (HMT) interdependence analysis to strictly identify the human agent interactions and resilience requirements. Explore the USMC's fire support coordination cognitive agent.

Recommendations for Further Research

Results from the first project team shows that more research is needed for the development and integration of joint CEC (JCEC). There is also further research needed in ad-hoc networks and connectivity of the joint forces. There is an urgent need for more research in artificial intelligence, machine learning algorithms and their integration into command and control systems. Research and development are needed to explore naval task force configurations that include joint forces capable of greatly extending the tactical span of control and effective mission range. Further classified research should be conducted for a comparison effort of the Multifunctional Information Distribution System (MIDS) Joint Tactical Radio System (JTRS), Link 16 versus Multifunction Advanced Data Link (MADL)-like communications and the use of MADL for the creation of a joint fires (JF) common situational awareness. MADL-like communication may require the upgrade of outdated mission processors and displays to handle the increases in information which MADL can provide. Research efforts concerning the speed of command, control, and communications needed for weapons engagement against adversarial hyper velocity projectiles is also another area of future concern.

For the second project topic, much remains to deliver a JF ISO distributed maritime operations that combatant commanders can count on. Analytic modeling should be used to evaluate all the new options, both technical and doctrinal. For instance, new fusion techniques can reduce the time to deduce target locations and sort decoys from real targets. Modeling those capabilities informs investment decisions. Most investments tend towards more platform or weapons, when often clever fusion can make current platforms and weapons more capable. Wargaming, especially for new command and control designs is a must. Only by talking thorough actual human activities can developers get a feel for whether the new ides have merit. More research needs to be done on other effectors. Kinetic effectors have decidedly obvious strengths, but perhaps the United States is looking to invite a de-escalatory off ramp, where a non-kinetic effect may be better at transmitting the strategic message.

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NPS-20-N038-A: Adaptive Data Flow

Researcher: Dr. Randy Maule
Student Participation: No students participated in this research project.

Project Summary

This project examined systems, processes and variables for dynamic information access to enable tactical decision makers to obtain a decision-quality picture for Command and Control in a Denied or Degraded Environment (C2D2E). This included scenarios for active management of the tactical situation (TACSIT), data flow paths, info classification, and releasability to allies. The selected approach provides multiple alliances with decision-quality data in real-time and with support for dynamic changes to information flows. Requirements were categorized into decision matrices and referenced to available systems and services.

Keywords: *command and control in a denied or degraded environment, C2D2E, tactical situation, TACSIT, artificial intelligence/machine learning, AI/ML*

Background

The Department of Defense is advancing new infrastructure to speed dynamic information to coalition allies. However, the technologies to achieve the desired effects and manage the data flows are still evolving. A research system tested for over a decade with naval forces established that portals with fine-grain information filters could support the coalition with real-time information and need-to-know data authorization (Maule & Gallup, 2010). This project extends this research to define new capabilities for decision-quality TACSIT in C2CDE scenarios. System variables and design considerations for adaptive data flows were presented and decision matrices developed to help determine the best available systems and services to achieve the desired information effect. Three research objectives were addressed:

1. Architecture variables to help ensure the correct data reaches the right person at the right time and at the right place.
2. System designs for dynamic information types and the means to secure and present data to stakeholders.
3. Enterprise deployment considerations for implementation and maintenance of the adaptive data flow services.

Findings and Conclusions

Architecture, workflows, systems and services advanced in this project support coalition TACSIT visualization and management. Multiple, adaptive routes for data transmission, with security and information classification at each level, and self-contained tactical operations help ensure decision-quality pictures in C2D2E scenarios. The implementation addressed sensor relay and processing, real-time streaming services, data science for near-real-time assessment, artificial intelligence/machine learning (AI/ML) for automation and predictive analytics, and distributed applications for tactical visualization and management.

Capability frameworks and decision matrices were presented to help assess adaptive data requirements, controls, and interfaces. In Phase 1, the capability matrices categorized required components for adaptive data flows. Capabilities were referenced against operations and metrics. In Phase 2, the system architecture was designed. New component capabilities from recent technical advances were investigated and designed into workflows. In Phase 3, the knowledge and service architecture were assessed. Capabilities, operations, systems, and services to support adaptive data flows were integrated into an overall solution with decision support matrices for the coalition scenario.

Recommendations for Further Research

This research established architecture, workflows, systems and services to support coalition adaptive data flows and real-time tactical situation (TACSIT) visualization. Future research may extend the architecture with additional processing capabilities to further enhance the event streams. The architecture may be applied to specific operational scenarios and training scenarios developed. Artificial intelligence/machine learning capabilities for analysis and automation may be extended.

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NPS-20-N054-A: Demonstration of Machine Learning Approach for Evaporation Duct NOWCAST as Part of Operational METOC Support

Researchers: CDR Joel Feldmeier USN, and Dr. Qing Wang
Student Participation: LCDR Josue Yanez USN

Project Summary

This project addresses several key areas: forecasting the evaporative duct (which is critical for predicting electromagnetic and electro-optical sensor performance as well as communications), understanding the feasibility of machine learning for short-time-range weather and ocean forecasting using data routinely collected by an afloat unit, and alternative organic prediction tools for meteorology and oceanography personnel afloat (who are dependent on output from ashore-run supercomputer models transmitted over high-demand but limited-bandwidth communications). Using several different “off-the-shelf” and widely-accepted machine learning algorithms, Navy approved software, and a personal computer with memory and processing power analogous to that currently used afloat, observations from a several-week field experiment (Coupled Air-Sea Processes and Electromagnetic ducting Research, CASPER-West) were used to make up-to-6-hour forecasts (i.e., a NOWCAST) of several meteorological variables, including the characteristics of the evaporative duct. When compared against persistence (i.e., assuming that the weather conditions will just stay the same as they currently are, a common test of forecast models), our

techniques showed enough skill for some variables to warrant further research although our results were likely limited by the relatively small size of the subset of data that we ultimately used for training and testing. Future work should include using more of the existing dataset (including electromagnetic and electro-optical related measurements), data from a related or similar field projects (e.g., CASPER-East), additional algorithms, and overall additional longer datasets.

Keywords: *Electromagnetic Wave Propagation, Evaporation Duct, machine learning*

Background

The original inspiration for this research was to couple the ever-more common use of machine learning and "big-data" predictive techniques in academia and industry with the information that naval vessels constantly gather about the environment. Radar and radio performance (and electro-optical sensors) are impacted by such factors as the vertical variation of atmospheric temperature and humidity, which are tied to larger-scale meteorological and oceanographic conditions. Ships at sea are particularly impacted by the evaporative duct, whose depth can vary throughout a day, causing variable sensor performance. Even before a ship, or group of ships, leaves port for an underway period, it turns on its radar and radio gear. The performance of this gear, which is effectively sampling the atmosphere at high frequencies (especially as compared to nominally hourly traditional weather observations), is a rich source of data about the natural environment that can be used for forecasting (see for example, Compaleo et al., 2021).

CASPER is a multidisciplinary university research initiative sponsored by the Office of Naval Research. During several weeks in the Fall of 2017, the CASPER-West field study took place off the coast of Southern California. Multiple ships, aircraft, small boats, buoys, floating platforms and shore stations with a variety of equipment took measurements of meteorological, oceanographic, electromagnetic, and electro-optical conditions (Wang et al., 2018). This dataset was used as it can serve as a proxy for both the traditional weather measurements ships have taken for centuries (air and sea temperature, wind, and humidity, for example), and non-traditional, but weather-affected, data such as radar performance.

Physics-based dynamic weather models run on supercomputers are the standard for forecast centers around the world, but their output can occasionally be difficult to download for forecasters on a ship. Shipboard personnel rely on such model output to run relatively simple aids in order to predict electromagnetic and electro-optical signal propagation. Secondary or backup methods of quantitative weather forecasting afloat are limited by shipboard computing power. However, some short-term forecasts called NOWCASTs (for example, the movement of a tornado; over periods of 6-hours or less into the future) may be amenable to the empirical/statistical techniques. Such methods are inherent in machine learning, which can be done on laptop or desktop computers.

The Python programming language is used by many in the machine learning community. Python is an open-source language, with many machine learning routines already downloadable, vetted, and in common-use by users around the world. Python is also authorized for use on Navy computers (J. Nelson, personal communication, June 1, 2020). Therefore, our goal was to sample from CASPER-West data as if we were on a ship operating in that area, taking observations, training Python-based machine learning algorithms with the observations, and using those algorithms as a backup (not replacement) method to make NOWCASTs. Although we focused on the evaporative duct, we also examined performance of variables such as wind and atmospheric pressure that would be useful for any short-term forecast.

Findings and Conclusions

The research here directly aligns with Oceanographer of the Navy interests in developing NOWCAST capability (D. McCarren, personal communication, March, 2020). NOWCAST techniques have limited windows of applicability that are not always clear a priori, and are expected to shift with variable type, weather regime, scales examined, and techniques used. The accuracy of those techniques is also academically interesting as it speaks to the level of expected variability in the meteorological and oceanographic environment over various time and spatial scales.

CASPER-West is overall a rich dataset. However, not all data was sampled continuously or with the same frequency. Ultimately, we chose to focus on weather and ocean temperature data from two buoys used during the experiment, sub-sampled to hourly values, and leaving us approximately 730 data times. We chose to divide our data into three sub-cases after noticing an early diurnal variation dominated pattern, a transition period, and then a Santa Ana wind event blowing from shore. In each case, 80% of the data collected was used to train algorithms, and 20% was used for testing and evaluation.

After a literature search, we decided to examine forecast results using multiple ML algorithms including the multi-variable linear regression, decision tree, random forest (which can be thought of as an ensemble of decision trees), and neural networks for short-term forecast. These algorithms are computationally quick, inherently probabilistic, and updateable in stride. In order to characterize our answers, we looked at metrics such as root mean square error (from CASPER observations). Observations were fed into the Navy Atmospheric Vertical Surface Layer Model (NAVSLaM) to provide a verifying truth for evaporative duct NOWCASTs.

New forecast techniques are typically compared to climatology or persistence environment. We trained machine learning algorithms to use one or multiple observations preceding a NOWCAST start time and then forecast out to 6-hours into the future. Persistence forecasts assume the variable of interest will stay the same from the observed value at the start of the forecast period out to the end of the period. All forecasts are compared against what was actually observed (or calculated from observations fed into NAVSLaM). Evaporative ducts were calculated in two ways: 1) machine learning algorithms were trained to NOWCAST the variables used by NAVSLaM, and then NAVSLaM evaporative duct height/evaporative duct strength were calculated; 2) machine learning algorithms were trained on evaporative duct characteristics calculated from observations, and then the algorithms could directly NOWCAST evaporative duct height and strength.

Results of our experiments were mixed. Some algorithms, for certain variables, outperform persistence forecasts. Values that we NOWCAST, with the exception of sea level pressure from a neural network approach, were physically plausible. This suggests, with further refinement, that simple techniques as carried out here can be useful for shipboard NOWCASTs.

Recommendations for Further Research

Machine learning techniques are most often coupled with "big-data." This initial demonstration was ultimately limited to several hundred observations available for training. Although not strictly defined here, a big-data scale dataset might be orders of magnitude larger (achievable for data collected at higher sampling rates). Therefore, an important next step in assessing the utility of machine learning techniques for NOWCASTs would be to use data subsampled at a higher frequency. Additionally, not all observations from the Coupled Air-Sea Processes and Electromagnetic ducting Research (CASPER)-West field campaign were used in this study. With more time, a training dataset of more variables collected at higher frequency could be assembled. CASPER-East was an additional field study on the U.S. East Coast, collecting similar data to the CASPER-West and could provide more cases for analysis. The value of NOWCASTs could also be examined in the context of decision models and a value of information framework, compared to climatology or persistence forecasts. This could be done with CASPER data, proxy data from historical records, or during another underway observation period.

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NPS-20-N069-A: Testing and Refinement of Bayesian Data Analytics for Tactical Prediction Capabilities in Data Denied Areas

Researchers: Dr. Wendell Nuss, Mr. Robert Hale, and Ms. Mary Jordan

Student Participation: LCDR Kellen Jones USN, 1st Lt Darby Maier USAF, and Brendan Lin CIV

Project Summary

Accurate environmental predictions are critical to tactical decision-making and mission success. Although numerical models of the atmosphere provide detailed depictions of critical parameters, their accuracy suffers in data-denied regions. Inherent errors can be reduced through post-processing using a variety of machine learning or statistical modeling techniques. In this study, a multivariate Bayesian non-linear regression approach is used to reduce surface wind forecast error with minimal observations used to train the model. Tests were conducted using forecasts of offshore wind events in Southern California. Results using only 10 observation sites for training the model produced error reduction across the entire domain.

Keywords: *battlespace environment, Bayesian ensemble model output statistics, BEMOS, Bayesian regression, forecasting, machine learning, model output statistics, MOS, numerical weather prediction, NWP*

Background

Predictions of environmental conditions are important for naval operations as they impact both mission planning and mission execution. Dynamically based numerical models of the atmosphere and ocean provide predictions of a large number of environmental factors that are important for naval missions.

These dynamically based models have inherent error due to a variety of factors, many of which are exacerbated in regions with limited observations.

Techniques to mitigate errors in numerical weather prediction (NWP) models have been developed to post-process the forecasts and reduce forecast error. The model output statistics (MOS) approach (Glahn & Lowry, 1972) uses multivariate linear regression techniques to relate forecast error to a set of model-predicted variables. This regression approach requires large amounts of observations and model forecasts to derive the regression equations. Recent post-processing approaches have used univariate non-homogeneous regression (Gneiting, 2014) as well as Bayesian statistics (Richter, 2012) to process ensemble model forecasts. Wendt (2017) used a Bayesian multivariate approach with a hierarchical parameter structure to significantly reduce error, even using limited training data.

All post-processing approaches require historical observations and forecasts to train the model, which are not available in data-denied regions. The Bayesian ensemble model output statistics (BEMOS) developed by Wendt (2017) has been shown to perform well with limited training data. Preliminary results show that as few as three days of training data is necessary to reduce error when the training days have similar characteristics. To optimize this approach to data-denied regions, longer-range, large-scale climate variations can be used to find analog training data. Critical to the use of climate variations to find analog training data is the ability to predict appropriate climate patterns in advance. The BEMOS model has been successfully applied to climate conditions associated with Santa Ana wind events in Southern California.

The objective of this study was to evaluate the ability of the BEMOS post-processing model to reduce forecast error using climate analog days for training. While use of analog days reduced the number of days needed for training, we also evaluated the performance of the BEMOS model when very limited observations are used in the training. These tests were done over the Southern California region for predicted Santa Ana wind events.

Findings and Conclusions

This study examined the application of a machine learning approach to reduce forecast error by post-processing numerical model forecasts of environmental conditions. The Naval Postgraduate School's BEMOS model was applied to low-level wind forecasts associated with Santa Ana conditions over Southern California. To determine the performance of the BEMOS model in data-denied areas, we ran tests using climate-predicted analogs and limited observations for training the model. These tests consisted of running a high-resolution regional forecast model on days predicted by a climate analysis using the same machine learning approach to be favorable for offshore flow over the Southern California region. The high-resolution forecasts provided detailed environmental conditions up to 36 hours in advance. The BEMOS model was then applied to the high-resolution forecasts using different training datasets to determine that best approach to reduce forecast error in data-denied regions.

To identify test days, the BEMOS model was applied to climate data to identify offshore flow days over Southern California. Climate analyses identified a characteristic long wave pattern associated with offshore flow over Southern California. This pattern could be predicted using the BEMOS model with the phases of the Madden-Julien oscillation as predictors. Results showed a high degree of success in these climate patterns as far as 21–28 days in advance. This technique was applied to historical data for November 2018 to create days to use for short-term forecasts to test the application of the BEMOS model to data-denied regions.

To test the application of the BEMOS model to our simulated data-denied region, a series of short-term forecasts were run on days identified by the climate analysis as offshore flow days. To simulate operational tactical forecasts, short-term forecasts out to 36 hours were done over the Southern California region on the 2–3 days surrounding six possible wind events. The error in these forecasts was assessed using over 400 observations in the region and averaged about 3.5 m/s over all the forecasts. Strong wind days that are of significant operational interest often had errors in excess of 5 m/s averaged over all the stations. To reduce this forecast error, the BEMOS model was applied to all the forecasts using three days of prior forecasts as training data. This was done with both the full set of 400+ observations and a data-denied set of 10 observations. In general, both applications of the BEMOS model reduced the error, although individual days varied with some days showing an error increase due to post-processing. These day-to-day variations in performance are most likely the result of the three prior days used in training as not being representative of the forecast test day. The most significant result was that the data-denied tests performed almost the same as those using all 400+ observations. This indicates that the BEMOS model can reduce error with a very small data sample to use for training the model. This could be improved by better matching the learning days to the test days to reduce the day-to-day variability.

Recommendations for Further Research

The results of this study indicate the value of post-processing environmental numerical model forecasts to reduce error. While we have shown that a very small number of observations can reduce error, the character of the error depends strongly on the similarity of the training days. Thus, we would recommend doing research to identify analog forecast days to use as training data. A machine learning algorithm could be applied to a series of past forecasts to select specific days that had similar characteristics. Our previous results suggest that if 3-5 analog days could be obtained, this would be sufficient to reduce error. In addition, the Bayesian Ensemble Model Output Statistics (BEMOS) model produces a full probability distribution of the forecast variable. This distribution should be exploited to give probabilities of winds or some other forecast variable to exceed some operational threshold. Probability charts of winds exceeding 10 m/s could easily be produced over the forecast domain, which could aid operational decision-makers.

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NPS-20-N078-A: Turkey, Great Power Competition and the Maritime Domain

Researcher: Dr. Ryan Gingeras
Student Participation: No students participated in this research project.

Project Summary
In recent years, the Turkish navy has assumed a more visible role in the making of Turkish foreign policy. In its pursuit of greater regional and global influence, Ankara has invested much in expanding and modernizing the fleet. While Turkish naval doctrine remains vocally committed to collective security and regional stability, other signs suggest that Ankara has assumed an aggressive agenda aimed at reshaping the status quo in the Mediterranean and beyond. Given the extensive changes witnessed in the fleet, as well as ongoing challenges within the armed forces and the country as a whole, it is difficult to assess the actual capabilities of the contemporary Turkish navy. A closer understanding of the aspirations and realities shaping the fleet, however, offers critical insights into the future of Turkey as a regional and global power.

Keywords: *Great Power Competition, GPC, Turkey, Russia, Black Sea, Mediterranean, Cyprus, Egypt, Greece*

Background
Turkish naval strategy has assumed greater prominence within elite political circles in recent years. To some extent, it reflects a broader reimagination of the country in historical and geo-strategic terms. According to this new line of thought, Ankara is obliged to pursue a maximalist approach towards its territorial waters (including claims to economic resources lying below the sea floor). Within this new framework, the United States is depicted as a rival and potential aggressor intent upon undermining Turkey's aspirations as a maritime power.

However, there are preciously few studies on the development of Turkish naval strategy or the role of the navy within contemporary Turkish foreign policymaking. Most of the research on the Turkish Armed Forces (TSK) are focused on land operations or the troubled history of the country's civil-military relations. It is only recently that Turkish popular media and think tanks have begun to focus on the development of the Turkish fleet. It is usually within the context of state issued publications, such as directives or policy statements, that the operational capacity of the navy is discussed. The data sets issued by the TSK, as well as the Turkish defense industry, remain largely unexplored by Western researchers. Nevertheless, despite these limitations, the recent growth in coverage of the Turkish navy does give strong indications that civilian and military leaders see the service as critical to the country's emerging strategic outlook.

Findings and Conclusions
In surveying the overall state of this literature, as well as delivering a closer analysis of the Navy's contemporary activities (both at sea and in development), this study intends to layout Turkey's growing aspirations in the maritime domain and how it perceives its place among other maritime powers (including the United States and Russia). Over the last decade, the Turkish navy is a force that has grown in both size and sophistication. Leading the way in this expansion has been the introduction of several

capital ships that were designed and constructed by local shipbuilders. By the end of this decade, Turkey intends to put more than a dozen new vessels out to sea. The largest of these ships, a light aircraft carrier, will likely enter regular service by the end of 2020. Augmenting this recapitalization effort are plans to equip new and existing vessels with natively produced weapons and detection systems.

However, the effectiveness of this new fleet remains difficult to judge, as much of it remains in development or has only recently entered service. More importantly, several obstacles and uncertainties plague the navy's immediate future. It is possible that the fleet may face problems of manpower in terms of shortages and training. Further aggravating this challenge are the political insecurities and purges that have plagued the officer corps. In addition to an ongoing "brain drain" among skilled engineers and designers, it is also clear that Turkey's defense industry is not completely capable of arming and maintaining ships without foreign assistance.

The original intention of Turkey's recapitalization program was to address shortcomings in the country's coastal defense. Increasingly, a broader set of regional ambitions play a role in how commentators and planners see the future of the Turkish navy. Foremost in Turkey's strategic interests is the desire to secure a commanding position in the development of natural gas resources off its southern coast. This desire to press for greater influence in the eastern Mediterranean comes directly at the expense of Greece and the Republic of Cyprus. Adding further weight to this claim is the December 2019 signing of a memorandum of understanding that recognizes a shared maritime border between Turkey and the Government of National Accord government in Libya. It is widely assumed Turkey intends to build a string of bases across the Mediterranean, as well as around the Horn of Africa. Yet like much of the Turkish fleet itself, very little in this vein has materialized.

Turkey's more aggressive posturing in the Mediterranean strikes a stark contrast with its behavior in the Black Sea. To Turkey's north, it appears that Ankara is intent upon maintaining a more muted stance with respect to Russia and regional security. While not formally distancing itself from the North Atlantic Treaty Organization's (NATO) strategic priorities, this tendency to mitigate against tensions with Moscow appears in line with Turkey's broader effort to leverage its relationship with Russia in order to maximize its influence and negotiating power on issues deemed imminently more important.

Recommendations for Further Research

Upon consultation with the sponsor, it is agreed that this study could be augmented by a greater research on the politics and capacity of the Greek Navy. As a member of NATO and an ally to the United States, Greece has long served a lynch pin for collective security and defense in the eastern Mediterranean. Greece's relationship with Brussels and Washington endures despite both historic ties to Russia and its fractious relationship with Turkey, a fellow NATO member. These ambiguities at the heart of Greek foreign policy have taken on new significance amid the evolving strategic landscape in the eastern Mediterranean. At present, Athens has sought greater assistance from the United States and its European partners in its effort to expand and modernize its navy. Greece's recapitalization effort is largely aimed at contesting what it believes is the increasingly aggressive behavior of Turkey in the Aegean and in the environs of Cyprus. Such efforts continue despite Athens' insistence that it remains a close friend to Moscow, whose own interests in the eastern Mediterranean has increasingly aligned with Turkey. Despite constituting a modest force within the context of great power competition, Greece's strategic significance and complex relations make its current maritime posturing a matter of vital importance to American interests. Therefore, our future research will examine the making of Greek maritime policy against this complicated backdrop.

NPS-20-N164-A: Shipboard Deployment Testing of Light Fidelity (LiFi) with Power Line Communications (PLC)

Researchers: Dr. Weilian Su and Dr. Donald Brutzman
Student Participation: LT Dimitri G. Paspalaris USN and LT Stephanie Robinson USN

Project Summary
Feasibility work on Light Fidelity (LiFi) data communications with Power Line Communications (PLC) and/or Power over Ethernet (PoE) is sufficiently advanced to merit integration of secure unclassified LiFi links aboard a Navy ship. Our research goal is to provide recommendations to the Navy on how to test and evaluate these technologies. Ongoing Naval Postgraduate School (NPS) research in Network Optional Warfare and shipboard LiFi has shown that light communication has the potential to decouple personnel networking from sensitive shipboard networking. Our methods included evaluation of PoE with LiFi onboard a hypothetical ship, and study of the process and procedure in acquisition and deployment of LiFi. The proposed research demonstrates that PLC and PoE can be integrated with LiFi and deployed onboard ship to carry out data logging, document downloading and chatting. In addition, radiation testing of PLC network during transmission was performed, which shows that PLC can be deployed inside a ship.

Keywords: *Light Fidelity, LiFi, Power Line Communication, PLC, shipboard, Light Emitting Diode, LED*

Background
LiFi is a new emerging technology that was proposed in 2011 by Hearld Haas, a German physicist (Haas, Yin, Wang & Chen, 2016). LiFi is a short-range wireless communication system that leverages the light generated by light emitting diode (LED) bulbs as the data transmission medium (Haas, Yin, Wang, & Chen, 2016). Unlike most visible light communication technologies, LiFi is a full-blown communications system like wireless fidelity. This is because LiFi has the following core principle building blocks: networking and protocols, interference mitigation and security, medium access control protocols, link-level algorithms, and channel modeling while maintaining the standard visible-light communication components (Mahendran, 2016).

LiFi is a technology that has many strengths that make it useful for the Navy and several commercial applications. For instance, the capacity that LiFi brings to the table is roughly 10,000 times more than the current limited at the radio frequency spectrum (Haas, Yin, Wang, & Chen, 2016). The projected speed for LiFi is estimated to be greater than 10 Gigabits/sec (Yaklaf & Tarmissi, 2019). Due to the short wavelength of light, which is in the nanometer category, information is more secure. Even though light can be reflected, refracted, and diffracted, the use of LiFi provides more security than WiFi. This is due to LiFi being less likely to be intercepted by an eavesdropping device. In addition, for the eavesdropper to exploit the information, it needs to have a clear line of site to the transmitter. In contrast to WiFi signals, which have much greater propagation in an obstructed environment, LiFi signals are less vulnerable to eavesdropping; the availability and efficiency for LiFi are better than current WiFi products because LED lights are cheap; they consume less energy; and most light fixtures can be retrofitted with LEDs (Noshad, & Brandt-Pearce, 2016).

LiFi can reduce significantly the electromagnetic radiation and tempest vulnerabilities, thus, lowering the probability of intercept as well as interference. From prior efforts on NRP project NPS-17-N091-C and NRP project NPS-18-N186-B, researchers have shown that LiFi can be combined with PLC using shipboard 120-VAC circuit to provide private and secure networks. In addition, LiFi can be integrated with PoE for quick shipboard deployment.

PoE emerged as a technology in 2003 that added further flexibility to Ethernet networks (Mendelson, 2004). An enabled switch provided power, in addition to data, over an Ethernet cable to any connected device. This allows a network implementer to connect networked machines and add access points without having to build a separate power outlet and accompanying powerlines to a space. PoE supports technologies like Voice over IP, video cameras, routers, small switches for devices sharing an uplink, intercom, access control systems, sensors, and LED lights (Chowdhury, Hossan, Islam, & Jang, 2018). Research has explored Ethernet as a backhaul for small cell networks where there is a high density of internet connected devices used in indoor environments (Ni, Liu, Collings, & Wang, 2013).

Findings and Conclusions (to include Process/Methodology)

Naval surface warships have typically upgraded onboard lighting systems to utilize LED fixtures that are themselves compatible with LiFi networking equipment. Both PLC and PoE offer the promise of avoiding separate cabling requirements; for example, existing lighting circuits and Cat5E cables can be adapted to support such networking without interference or impacts with other ship systems. Also, both PLC and PoE integrations with LiFi were investigated and analyzed to provide methodologies and results for shipboard deployment.

The integration of PLC and LiFi is simple, and the format is almost a plug and play style format, which means it is easy for end user implementation. The proposed analysis and evaluation are relevant to U.S. Navy shipboard electrical lighting infrastructure; onboard ships currently, there are two power configurations: 450 V, 60 Hz three-phase alternating current and 120 V, 60 Hz three-phase alternating current (Naval, 1998). The power to the lighting distribution network comes from an electric generator and then is converted down from 450 V, 60 HZ to 120 V, 60 Hz via a lighting transformer (Naval, 1998).

For analysis, the Luminex LiFi unit integrated with shipboard lighting and shipboard cable. Different PLC units (Netgear, TP-Link, and D-Link) were tested. Performance results of using TP-Link PLC is around 1.95 MB/s transmission rate and 2.81 MB/s receiving rate, which indicates the transmit and receive data rates are enough for online chatting, data logging, and document downloading. The performance of Netgear and D-Link PLCs is around the same as TP-Link. In addition, the electromagnetic radiation of the power line is around -50 dBm at 0.15 m and -65 dBm at 1 m, which corresponds to 1e-8 W and 3.16e-10 W, respectively.

As for the integration of PoE and LiFi, CAT5 or CAT6 Ethernet cable is needed to connect the LiFi access point to the PoE switch, and then, for ships that do not have PoE enabled switches, to the existing shipboard Ethernet backbone. In addition, a Virtual Private Network technology that is listed on the Department of Defense Information Network Approved Access List can be used to increase security.

For a hypothetical USS Underway ship, 74 LiFi devices are needed: 3 for officer stateroom; 4 for office; 20 for passageway; and 47 for crew mess. There are myriad factors to consider for achieving rapid and efficient deployment of LiFi in a shipboard environment, including an adopted light communications standard for achieving enough technology maturation for approval by the Department of Defense acquisitions system. There are no major acquisition barriers for deploying LiFi, but careful planning and coordination at the program manager level is important to ensure timely fielding to prevent budgeting problems impacting program success. A comprehensive site survey to determine the most optimal locations for LiFi access points is also required to determine if there is any difference from Consolidation Afloat Network Enterprise System wireless access point placement and assess special requirements for designated ship spaces unique to each ship class.

Recommendations for Further Research

The following is a list of recommendations for future research to further enable Light Fidelity (LiFi) deployment: test another commercial LiFi product such as PureLiFi and conduct performance testing; take integrated LiFi panel from Naval Postgraduate School lab and conduct testing onboard an actual U.S. Navy ship; look at different modulation schemes for LiFi or Power Line Communications (PLC) units to see which techniques have the best performance; re-create the U.S. Navy unclassified or classified network architecture, and apply LiFi and PLC technologies to the architecture and see how the communication technologies effect the network; find solutions for ceiling heights greater than 18 feet for hanger bays and well decks; investigate light communication channel using only red-light Light Emitting Diode or use on the bridge and hallways during night hours when white light can't be used; test LiFi performance in smoky environments to determine thickness and particle levels that can degrade communications capability; and evaluate the use of ultraviolet light for killing germs as well as light communication.

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NPS-20-N214-A: Cyber Warfighting System for Resilience and Response

Researchers: Dr. Scott Jasper and Mr. Jack Turner
Student Participation: CPO Carlos Rodriguez-Reyes USN, CPO Jason Sauerbier USN, and SSgt Coby Roscoe USMC

Project Summary

The Cyber Warfighting System (CWS) project aims to provide an automated capability to recognize and declare the threat in order to set appropriate resilience and readiness postures. The challenge today is that enterprise cybersecurity product vendors are moving to architectures that leverage cloud-based resources to offer advanced capabilities powered by real-time threat intelligence, big data analytics, and machine-learning algorithms. Due to operational requirements and constraints, tactical Department of Defense (DoD) networks experience frequent and prolonged periods of isolation from external network services, affecting the connectivity needed by cloud-centric cybersecurity platforms. Therefore, the CWS project studied and analyzed the performance of a cloud-centric cybersecurity platform under cloud-connected and internet protocol (IP) isolated conditions; the platform performed against an adversary emulation using the MITRE ATT&CK framework in a specifically constructed Naval Postgraduate School (NPS) lab architecture. In the IP-isolated condition, the installed Palo Alto Networks Cortex XDR agent, which uses local machine learning based upon a model trained in the cloud and updated when connected, along with local behavioral threat protection, successfully detected 12 incidents, primarily related to PowerShell and Macro programming language execution. The detections were similar in the cloud-connected condition, although the full extent of the Cortex XDR services was not tested due to the experimental design that limited agent exploit prevention opportunities, network behavioral analytics, centralized data storage, and event stitching across multiple network and endpoint devices. There were some observed differences in the two conditions, primarily, the reporting of artifacts, the correlation of alerts, and the visualization of incidents, which could be useful to cybersecurity engineers in implementing and utilizing cloud-centric products for incident management in tactical DoD environments, especially for ships underway or marines in the field.

Keywords: *resilience, response, cybersecurity, machine learning, behavioral analytics*

Background

Today massive numbers of uncorrelated and unprioritized alerts overwhelm network security operations. A different approach is needed, one that can operate effectively at network scale and attack tempo against sophisticated techniques, to defeat an adaptive attacker before damage is done, while maintaining operations. This approach requires an automated architecture that fuses endpoint solutions with network-and cloud-based capabilities, such as centralized threat intelligence gathering and distribution. Endpoint solutions discover and analyze technical operations, such as new unique processes or unusual network flows, for suspicious and malicious behavior. In practice, they protect against malware, Fileless attacks, misuse of legitimate applications, and abuse of stolen credentials. Ideally, the automated architecture would reduce the number of alerts that require manual interpolation to a manageable level and correlate information across attack vectors enabling operators to react at attack tempo.

NPS has performed research with industry on understanding multiple aspects of resilience and response. The research led to the creation of an automated cyber defense use case to demonstrate the technical feasibility of emerging commercial capabilities in a difficult scenario, such as the use of evasive tactics seen in global campaigns featuring ransomware. Most ransomware applications finish the encryption process in less than a minute, far too quickly to be countered by manual intervention alone. Palo Alto Networks was chosen for the demo since many of its existing commercial capabilities are installed at NPS. The demo employed the Circadence virtual cyber range to depict architecture results against live WannaCry ransomware. The Palo Alto Networks' Traps endpoint prevention modules proved capable of blocking several execution processes. The demo was shown at Integrated Cyber at Johns Hopkins University in May 2018.

In the two years since the demo, the cybersecurity industry has become cloud resource dependent. Most advanced security industry solutions now require continuous connectivity and data transport to cloud-based systems for threat analysis, correlation, characterization, and remediation. The problem is the U.S. Navy and Marine Corps is unable to fully utilize these cloud-based services due to security concerns with data leaving DoD networks or while operating in denied environments with often limited or no IP connectivity. The CWS project created a lab environment at NPS to study and analyze potential impacts when cloud-based cybersecurity platforms that provide signature-based and behavioral based techniques combined with machine-learning algorithms are employed with deployable military units. Three NPS masters students in Applied Cyber Operations (MACO) chose as their capstone project to study and analyze the performance of a cloud-centric cybersecurity platform, while both connected to its native cloud resources and while IP-isolated, simulating the loss or degradation of internet connectivity (Roscoe, Sauerbier, & Rodriguezreyes, 2020). They hypothesized that the differences between a cloud-centric cybersecurity product operating under the two different conditions could present themselves in the detection, analysis, correlation, reporting, and visualization features of the product.

Findings and Conclusions

The purpose of the CWS study is to inform topic sponsor command requirements articulated in the Integrated Navy Operations Command and Control System (INOCCS) Framework. The INOCCS Framework serves as the reference model on which to base the classification and analysis of tools. The CWS study aims to address gaps in tools in these functional domains: decision analytics–data aggregation and synchronization; decision analytics–machine learning; and visualization–dashboards. The CWS study will aid in mission accomplishment by implementing tools that are necessary for comprehensive Situational Awareness and Command and Control of Department of Defense Information Network-Navy (DoDIN-N) elements and capabilities.

The CWS project created a system architecture in an NPS lab that represented a common U.S. Navy and Marine Corps network to study and analyze the security performance characteristics of IP-isolated and cloud-connected conditions. The system architecture consisted of virtual endpoints installed and configured on physical servers along with the Palo Alto Cortex XDR security platform. The MACO students conducted attacks on the network by a non-autonomous, automated adversary emulation of the Chinese Advanced Persistent Threat group (APT3)/Gothic Panda, using the MITRE ATT&CK framework and the MITRE CALDERA tool kit.

In the IP-isolated condition, the students removed all external connectivity and conducted the adversary emulation, recording detection alerts and obtaining log data from the local security agent console. Following adversary emulation, they restored connectivity to the IP-isolated environment, allowing the endpoint agents to communicate with the cloud-based resources. In the cloud-connected condition, they maintained all external connectivity while conducting the adversary emulation, recording detection alerts and obtaining log data from the local security agent console and the cloud resources. Under both conditions, the agents were configured to operate in the alert-only mode.

In total, 76 separate APT3 emulation events were conducted against the Windows 10 endpoint and Windows Server 2019 domain controller. The IP-isolated condition detected 9 of the events launched with 7 detections on the endpoint and 2 detections on the domain controller, with a total of 12 separate incidents. The cloud-connected condition produced 10 detection events, 8 on the endpoint and 2 on the domain controller, with a total of 13 separate incidents. In addition, the malware detection on one of the events yielded different results in that the cloud-connected condition labeled the fatrat.exe executable as malware, whereas the IP-isolated condition did not provide a determination.

The emulation results confirmed original expectations that the IP-isolated condition could detect advanced adversarial techniques through local machine-learning analysis along with local behavioral threat protection, but the cloud-connected condition would provide for greater detection through automated static and dynamic analysis of files in a centralized threat intelligence platform. In addition, the students found the reporting of artifacts for automated analysis, the correlation of related threat alerts into discrete incidents, and the visualization of these incidents on the web interface were inconsistent between the two conditions. These findings support the hypothesis that differences between a cloud-centric cybersecurity product operating under the two different conditions could present themselves in features of the product.

Recommendations for Further Research

The Cyber Warfighting System (CWS) study informed topic sponsor command requirements regarding gaps in Integrated Navy Operations Command and Control System Functional Domains. The performance disparities between the internet protocol-isolated and cloud-connected conditions should be considered by cybersecurity engineers in implementing and utilizing cloud-centric products for incident management in tactical Department of Defense environments. Recommendations for further research center on expanding the scope of the system architecture. The COVID-19 pandemic complicated the initial objectives of the CWS project due to movement restrictions that prevented physical access to the servers. Therefore, a significant part of the effort was devoted to constructing the virtual environment and configuring the adversary emulation platform. The original project design contained a greater number of endpoints to make use of Cortex Analytics. The analytics engine identifies a baseline of normal behavior on the network to notice abnormal behavior. Inclusion of this capability would have allowed assessment of any differences in detection by learned behavior patterns within the connected environment. Likewise, the small scope of the test affected the ability to test the Cortex Data Lake. The Data Lake is a centralized storage location for all logs generated by Palo Alto Networks security products. The Data Lake is utilized to access, analyze, and report on network data. Study and analysis of the conditions at a larger scale with more data aggregation may reveal pertinent network data analysis. Lastly, other Advanced Persistent Threat groups with varying capabilities could be emulated.

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NPS-20-N238-A: Using Virtual Environments and 3D to Assess Issues Related to JF ISO DMO

See: NPS-20-J315-A: Integrating Joint Fires in Support of DMO with Focus on Integrating Unmanned and Conventional Fires

NPS-20-N313-A: Data Strategies in Support of the Naval Operational Architecture

Researchers: Dr. Arkady Godin, CAPT Scot Miller USN Ret., and CDR Sue Higgins USN Ret.

Student Participation: No students participated in this research project.

Project Summary

In the 21st century, information warfare promises to be a crucial component in a war winning strategy. The Navy is therefore adopting to a new operational architecture, one that supports information warfare. However, supplying the data that provides the essential building blocks of information requires a 21st century data strategy, one that recognizes the great strides in data processing achieved over the past few decades. This research intends to develop a roadmap for the Navy to consider employing as a part of the emerging Naval Operational Architecture (NOA). At the Navy level, we envision a near-, mid-, and far-term set of objectives and components of a data strategy. The near-term approach is designed to use commercial-off-the-shelf /government-off-the-shelf products to leverage cutting-edge storage, ingest adaptive workflow automation, and mature Deep and Reinforcement Learning technologies to advance Maritime Situational Awareness. The mid-term will focus on an ontological knowledge base, representing dynamic battlespace situations, and "what-if" battlespace simulated scenarios. We anticipate the far-term will focus on transferring human activities to Artificial General Intelligence (AGI); however, AGI requires a significant sequence of scientific breakthroughs which will require strategic investments.

The major finding of the research is a realization that the right way to manage knowledge is not at an observation level, but at a situational level. This major study discovery makes it possible to move away from approaching knowledge as objects (or entity-nouns) but thinking about knowledge at a "situation" level of abstraction allowing mixing facts represented by objects, with events (states, actions, ad-hoc

environmental conditions). This realization allows us to view the world as it is in motion, rather than through static snapshots.

Keywords: *ingest, adaptive, workflow, automation, deep, reinforcement, learning, ontology, situations*

Background

To remain competitive in the great power competition, the Navy is emphasizing Information Warfare as the force multiplier of the NOA. The Navy's current approach to data is based on platform or mission-centric thinking, which has resulted in the build-up of data siloes, preventing the use of tactical data by all relevant users. There have been numerous data-strategy development efforts in the past, built around operational needs which were, in most cases, quite modest. These data strategy efforts were accompanied by the advent of some new computational approaches (i.e., Service Oriented Architecture). The core mission of the data strategy has now shifted from entity tracks, to adapting to events in dynamic contexts of battlespace situations which evolve in a rapidly changing world. Prior strategies focused on accessing semantic web triple stores of static world views, rather than adapting to events and corresponding facts which depict dynamic world views. The most critical components of the NOA will be bleeding-edge, innovative data strategy and data-processing architecture, along with being scalable, fully integrated, and without stovepipes. As such, the current evolution of Naval capability must include integrated, scalable and resilient storage, memory, access, and processing capabilities. Enabling infrastructure must be based on commodity offerings from industry tailored to support unique workloads of machine learning (ML), deep learning (DL) and artificial intelligence (AI) technologies to provide timely cognitive support to the warfighter.

Findings and Conclusions

This study explored the emerging NOA design and data strategy requirements to enable an innovative information warfare strategy, which will ultimately result in a competitive advantage over our peer adversaries. As stated above, a state-of-the-art data strategy must be scalable, resilient and adaptive, allowing advanced ML, DL and AI functions to execute via end-to-end analytical workflow pipelines that automate mediation and orchestration of increasing quantities and varieties of disparate data sources, types and formats. The pipeline will include data ingest, load-for-integration and learning, and inferencing to achieve and maintain the tactical advantage. The objective is to enhance situational awareness within the Observe-Orient-Decide-Act loop by inserting mathematically based courses of action (COA)-development technologies with "projection of future states." This results in multi-party, multi-domain, and cross-organization wargaming intelligence, which enables both machine and human understanding of an operational battlespace via disclosure of cognitive decision cues.

Our process and methodology consisted of an approach that climbs the Data–Information–Knowledge (DIK) pyramid. Our findings were directed by the topic sponsor to be limited to just "Knowledge" without mixing it up with "Knowledge Understanding." Therefore, our research team focused on bottom-up data strategy research without any interference from operational signals like human-defined Commander's Intent or Human Machine Teaming interface-based COAs.

Our findings on a Data Ladder in the DIK pyramid led us to conclude that for the data strategy to hold, it must include a robust cloud-based affordability strategy. As cloud-based architecture provides a scalability guarantee, our research concluded that if outside pay-as-you-go cloud components are used, there must be a "universal" storage cache component. This universal requirement demands a "canonical format" representing 80/20 of base formats utilized in the NOA. Data architecture that doesn't follow this data strategy tenet is destined to be either unaffordable, or unscalable and non-performant.

Further, our findings on the Information Ladder in the DIK pyramid led us to conclude that the Information Ladder must be based on a variety of typing systems. This will add key abstractions to the archetypes, including noun-entities, interactions between noun-entities, events including states, actions and ad-hoc events, and situations and concepts. Investing into typing systems derived from ontologies is critical to not only the Information Ladder, but also to the Knowledge Ladder in the DIK pyramid. We also see a utility for a disciplined approach which the Smart Information Dynamic Catalog designed on clouds is bringing on board. That is, the Information Catalog does not just manage data and metadata. It also maintains a mapping between data and metadata, and physical and logical file groupings.

Our findings regarding the Knowledge Ladder combine the epitome of earlier efforts, plus unique knowledge-centric strategic vectors. The foremost need is to invest into the Knowledge Representation (KR) with a role of capturing reasoning over heterogenous and integrated knowledge archetypes at different levels of abstractions. Our research team concluded that all knowledge must be accompanied by appropriate event sequences, as this is the only possible mechanism to aggregate heterogenous events which accompany appropriate archetypes. Per David Bohm (1980), event sequence-based integration is a recipe against the fragmentation of world views, in a pursuit towards the wholeness of world views. Success in cross-archetype aggregation will ensure the resultant event sequences will both be properly sequenced and analysis-ready via causal inference. Making this happen will revolutionize the field of decision making.

Recommendations for Further Research

The Communication with Computer and Machine Common Sense programs at the Defense Advanced Research Projects Agency have successfully invented Visual Commonsense Graphs (VCS), which offers a fascinating path forward. In addition, scientists from the Paul G. Allen School of Computer Science & Engineering, and Allen Institute for AI, combined what-if rules for various inferencing event types, crowdsourcing and Generative Learning. They were able to generate different commonsense events by leveraging natural language processing and multi-media data sources. Given these advancements, our team recommends further research in applying event generation techniques to battlespace situations, with a goal of achieving "logical access" to Knowledge Representation archetypes. If VCS shows its strengths by "logically" (not physically "as is") accessing battlespace situations, this will be a major step in a cross-archetypes aggregation required for decision-making superiority.

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NPS-20-N349-B: Leveraging Blockchain as an Autonomous Unclass Software Distribution Support

Researcher: Mr. Peter Ateshian
Student Participation: LCDR Dwijayanto Nur Endah FORNATL IND

Project Summary

The United States Navy seeks to leverage emerging technologies to manage massive amounts of data from multiple geographically separated systems. The Navy is aware of the importance of data usage and data transfer in supporting its operations; however, data management requires a data transfer system that is safe, fast, and scalable. The Automated Navy Unclassified Software Distribution (ANUSD) is an application for provisioning and delivering software to all nodes on the Navy's enterprise network based on BlockChain Technology. In this research and thesis, we performed critical comparisons of Public BlockChain and Private Blockchain with the aim of determining which one would perform better in conjunction with ANUSD. This research applied rigorous simulation testing to several theoretical predictions, and as such, the two principal research areas were divided into BlockChain Merkle tree theory and systems architecture. Data was collected through simulation in both portions, and two basic categories of BlockChains were identified, deployed, implemented and measured in software as cloud distributed applications (Dapps). We compared locality of BlockChain implementations on distributed computers, such as laptops and Amazon Web Services (AWS), as a cloud-based solution. We used an IBM Hyperledger (Private BlockChain) network and an Ethereum BlockChain (Public BlockChain) network as the basis of the comparative analysis of their latency and scalability. We also compared the transactions per second (TPS) achieved with Ethereum against that of Hyperledger with the ANUSD application installed. The results showed that as we scaled up the Ethereum network, there was a significant increase in TPS. In contrast, increasing scalability did not have a significant impact on TPS for the Hyperledger Network. Maintaining time synchronization, such as NTP IEEE 1588 standard, is easily facilitated on AWS, whereas distributed and possibly distrusted computers or laptops require an exact standard time reference, and real time clock drift is not easily mitigated. Although transaction times were faster on distributed computers as there was no virtualization degradation and security overhead with Dockers and Containers. The BlockChain synchronization and additional security in Private AWS instantiation proved to be a more reliable, via redundancy, and more portable solution. The conclusion formulated in this report is based on the results of the experiments on the implementation of the ANUSD in the Ethereum and Hyperledger private networks. The conclusions are also based on the chart summarizing latency (transactions per second) obtained from the tests conducted in this research and what was observed about the effect of scalability on latency.

Keywords: *systems engineering, information sciences*

Background

BlockChains are being proposed to allocate the 6G Frequency Spectral domains in real time. This technology is being developed at the Naval Postgraduate School (NPS) for the Energy Academic Group in the Distributed Security of renewable energy micro grids. The currency is Q, Coulombs or Charge, where the Producers or PV, Generators or Thermal sources supply it, and it is then stored and available for consumers. As Supervisory Control and Data Acquisition systems are a centralized power grid management system, they have a single point of security failure. National Institute of Standards and Technology has documented these failures and suggests an alternative, such as a distributed or parallel solution. In 2017, NPS developed an Ethereum private blockchain leveraging the Distributed Ledger Technology (DLT) with a Scholarship for Service student. We developed both wireless and hardwired versions of these private Layered dual BlockChains. An attacker would have to be successful in a simultaneous denial of service (DDoS) attack to own more than 51% of either BlockChain independent private network. Our Smart Contract with enforced policy transactions were in the order of microseconds, using low-cost Raspberry Pi3(RPi3) nodes and Linux Laptop miners. These Proof of Work (PoW) Ethereum Nodes were using Mist and Truffle for wallets and infrastructure. Hyperledger, IBMs BlockChain was slower, and proved to be more onerous and less flexible than Ethereum and could not be easily deployed on low-cost nodes like the RPi3. We then tried virtual machine (VM) implementations on IBM's Watson and local laptops; however, the transactions times were 10s of seconds—six orders of magnitude slower than the Ethereum, Mist & Truffle system. In related work, two Marine Corps' students have taken the RPi3 six node Ethereum BlockChain system and are using it for a dual thesis on the security of the Military Service Member PII and HIPAA data. We eliminated several distributed BlockChain issues such as synchronization and wireless noise by deploying our BlockChains on an AWS cloud. This architecture and deployment mitigated the BlockChain time synchronization and improved the transaction times. With a hardwired AWS cloud collocated BlockChain platform, we reduced the attack surfaces for hackers and reduced the wireless disruption potential for distributed denial of service (DDoS) attacks.

Findings and Conclusions

ANUSD on Private IBM Hyperledger Fabric Network

Hyperledger Fabric's performance is largely dictated by implementation issues (API overhead, consensus algorithm implementations, capabilities for tuning, architectural overhead [Docker]) rather than theoretical limits. Hyperledger Fabric still lacks a fully robust consensus algorithm, but IBM is working towards Practical Byzantine Fault Tolerance (PBFT). The latest version (2.1) includes an algorithm that provides crash-fault tolerance but not PBFT. Due to its flexibility (support for permission users and different consensus algorithms), it theoretically provides far greater opportunity to optimize and achieve higher transaction rates compared to proof-of-work schemes because the latter allows the consensus algorithm to be tuned per the unique trust-topology of each business problem. However, the Hyperledger Fabric is very unstable, and the system breaks down suddenly without warning. In addition, the documentation contains an abundance of information, but it is mostly theoretical, rather than practical, and the product is made considerably slower by IBM's security architectural choice to base it on Containers (Dockers). In the long term, this choice makes sense, as it is easier, to deploy and operate the Hyperledger network once it is stable.

ANUSD on Private Ethereum Network

AWS Medium is limited to central processing unit (CPU) credit because the Tier 2 Medium has burstable performance and has a CPU credit limitation. Hence, in testing, when the miner reached the CPU usage limit above the performance limit, the performance dropped to the point of 20% usage on the second miner. This greatly affected the TPS calculation for above 1,000 iterations in Tests B and C. The test process for calculating latency by using the caliper on the Ethereum network did not work smoothly: several bugs were encountered, and the caliper was not stable. Therefore, it was decided to use artificial test tools by using additional Python code. The test tool file is available in the installation package file.

Recommendations for Further Research

The results of this work identified several opportunities for future research. For example, engineering prototype work to support field testing of these results could explore the ability to deploy the research presented in this thesis on the implementation of Automated Navy Unclassified Software Distribution (ANUSD) on a private IBM Hyperledger and a private Ethereum blockchain network is limited to a comparison of the latency block time (transactions per second) on the two networks. Due to limited time, this research could not make similar comparisons of other factors.

Future work to expand or supplement this research could include comparing cyber security on these networks. Security is an important factor for consideration and requires an accurate comparison of results from the two networks in supporting the ANUSD to be built by the United States Navy. Such research will be a valuable reference for decision makers in determining which network to choose for the ANUSD of the United States Navy system.

Specifically, the first security factor that can be explored is confidentiality in relation to the implementation of ANUSD on the two networks. Confidentiality is one component of the Cyber Security Triad, and it supports security in implementing an application on an internet network. With confidentiality, we can ascertain whether the data managed as a BlockChain payload, which is sent between fellow nodes, cannot be glimpsed or compromised by other parties who are not part of the core BlockChain private hardwired cloud network.

The second security factor that can be explored is integrity in relation to the implementation of ANUSD on the two networks. Integrity is another component of the Cyber Security Triad. Applications used for an internet network must be ensured not to be vulnerable to Man-in-the-Middle Attacks. With this type of attack, the attacker not only compromises confidentiality, but can also make changes to data sent from one node to another node. An attack on the network's integrity is much greater in severity as compared to an attack on the network's confidentiality. Therefore, the comparison of the integrity of the ANUSD on the two blockchain networks is an important area for future work and can also serve as a reference for United States Navy leadership. Finally, system overall availability can also be explored. For example, it would be valuable to compare the availability of the implementation of ANUSD on the two BlockChain networks.

NPS-20-N366-A: Understanding the Sources of Illicit Drug Bale Wash-up

Researchers: CDR John Joseph USN (ret.), Dr. Tetyana Margolina, Dr. Leonid Ivanov, and Dr. Timour Radko
Student Participation: LCDR Alaina Ramsaur USN

Project Summary

Counter-drug agencies have encountered many illicit bales of drugs wash up on beaches around the Gulf of Mexico region, yet it is not clear where the packages originated or how long the packages had been drifting. Cases have almost quadrupled in the past few years. This study applies high-resolution oceanographic modeling to provide a physics-based solution that narrows the likely origins of the washed-up drug bales and sheds light on their "patterns of life." The study integrates critical intelligence information collected by the U.S. Coast Guard, the Drug Enforcement Agency, Joint Interagency Task

Force (JIATF) South and other drug enforcement agencies to help guide and constrain the model to produce statistically significant, realistic output. Two modeling approaches were used. A forward-motion approach uses an initial cluster of simulated bales driven by modeled currents and wind stress to gauge where and when bales would reach known wash-up locations. A backward-motion approach simulates bales moving along tracks from their landing locations driven by time-reversed model physics. Information based on the insight of experienced "on-scene" enforcement personnel provided constraints on how the model results are interpreted. Intercepted bales jettisoned from Go-Fast boats or airdropped at specific locations and times can be used to validate the model output. Ensembles of hundreds of model runs are conducted to provide statistically valid results for the study. Results provide insight on the methods used by drug smugglers to move their illegal cargo. Forward modeling showed eight principal paths of transport from Mexico to the U.S. coastline. Seasonal variability significantly affected wash-up locations. Time-reversed modeling combined with known landing locations demonstrated that potential source locations can be identified based on ocean model physics. Trajectory results are quite sensitive to turbulent diffusion and more ground-truth information is needed to determine the optimal values to improve overall model performance.

Keywords: *counter drug, drug bale wash-up, adjoint ocean modeling*

Background

Counter-drug agencies have observed an increasing trend in illicit drugs packaged in bales washing up on shore of beaches in Florida, Texas, Louisiana, Alabama and Mississippi and the eastern shore of Mexico. However, determining from what country these bales originated has puzzled these agencies as no one has been able to dedicate the time or effort to research the possible origins and ways these bales come to be floating in the sea. This trend has almost quadrupled in the number of cases in the past few years, but it is not known why. The counterdrug community can learn much from a study into the trends and patterns-of-life. For example, information about the packaging and marine growth on the package can provide insight into whether the packages were originally air-dropped or transported by boat. Markings on the packages can provide hints of their original source or if they are connected to interdictions at sea by the U.S. Coast Guard (USCG) or the Drug Enforcement Agency (DEA). Incorporating oceanographic models to help determine the drift patterns of the bales once released can help "connect" a bale's wash-up location to its potential release position and transport time. The USCG has documented geographic positions, dates, times, photos of each of these cases over the past four to five years. Combining this information with realistic ocean physics from models is anticipated to paint a much clearer picture for counter-drug agencies on how bale wash-ups are directly related to their sources.

Findings and Conclusions

This study can be divided into four subsections. First, we applied the 2019 surface circulation calculated by a high-resolution hydrodynamic model, Regional Navy Coastal Ocean Model (RNCOM), to solve the forward-motion problem to understand the physical mechanisms of drug bale transport from deep waters into shallow waters and then onto the U.S. coastline in the Gulf of Mexico region. Additionally, we applied Ivanov and Chu's (2019) technique to understand how much dynamical chaos contributes to the packet transport. Second, we solved the backward-motion (time-reversed) problem to understand the physical mechanisms of the transport from the shallow waters and U.S. coastline to places where they were initially deployed. Third, we identified the potential locations where the packets could have been deployed. Fourth, we had to understand how turbulent diffusion can influence the dispersion of the packets. Note that the turbulent diffusion may be generated by the deterministic chaos as well as non-coherent Kolmogorov's diffusion. The second type of diffusion was considerably weaker than the diffusion generated by the deterministic chaos.

The forward problem: We calculated approximately one thousand particle trajectories within a three-month period using high-resolution (1/30th degree) nonlinear circulation in the area of interest from RNCOM. RNCOM assimilates available quality-controlled observations of temperature, salinity and sea surface height and uses 1/12th degree Hybrid Coordinate Ocean Model (HYCOM) output as boundary conditions. Calculations at a depth of 2m demonstrated the existence of eight principal paths for transportation of drug wash-ups from a domain near the Yucatan Peninsula to the U.S. coastline. The modeled circulation was very nonlinear. Therefore, it is reasonable to assume that the deterministic chaos should intensively contribute into deterministic turbulent diffusion at mesoscales. We use the results from Ivanov and Chu (2019) to estimate this turbulent diffusion. From the analysis of Lagrangian trajectories, it was concluded that particles deployed near Belize moved with the Gulf of Mexico surface currents, and they reached the U.S. coastline approximately within three months. Seasonal environmental conditions made significant impact on the distribution drug-bale wash-up locations. Drift onto the coastline is due to tide flows, winds and mesoscale variability. Wind waves and other types of waves were not accounted for in the drift of drug wash-ups events.

The backward problem: Intelligence information received via the USCG District 8 and the dialogue with some of the on-scene counter-drug personnel helped us identify common bale wash-up locations. Our numerical experiments demonstrated that to reach the U.S. coastline, the drug bales could be deployed near Belize in the geographic area limited by the Mexico coastline on the west and along 22.5°N, identifying this as an area of possible bale deployment. Additional studies using this model are needed to identify other possible likely sources of bale deployment.

Turbulent diffusion: The choice of the Kolmogorov-type turbulent diffusion coefficients with small spatial scales is challenging in physical oceanography. We found our trajectory results are quite sensitive to this parameter and we need more ground-truth information to determine the optimal values to improve overall model performance.

Recommendations for Further Research

Our present investigation lays the foundation for further work on methods to improve estimations of how the drug bales are moved through the ocean by environmental factors and tend to wash up at some common locations. There is more work to be done to fine tune the model in terms of turbulent diffusion coefficients, applying appropriate drag coefficients, and validating the results with data from the field. Due to COVID restrictions on travel, we were not able to conduct the validation tests we had envisioned for this project. However, we have a student with experience in this work while assigned to 4th Fleet and feel confident that we will be able to improve the model to allow operators to use this tool confidently and successfully.

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N3/N5 - Plans & Strategy

NPS-20-N068-A: Great Power Competition and Strategic Deterrence – Russian New Capabilities Impact on NATO and the U.S.

Researchers: Dr. Mikhail Tsypkin and Dr. Jeffrey Larsen

Student Participation: No students participated in this research project.

Project Summary

The study supports the work of N514, which concerns strategic missions of the US Navy. The Navy must determine where and how best to allocate its limited resources in developing a strategy and response to rising threats in an era of great power competition. In 2018 and 2019, Russian President Vladimir Putin unveiled a number of “exotic” new weapons to be deployed by the Russian military. These weapons included a hypersonic glide vehicle for Intercontinental Ballistic Missiles (ICBM) (Avangard), a super long-range torpedo armed with a nuclear warhead (Poseidon), a nuclear propelled and armed cruise missile (Burevestnik), an aero-ballistic missile (Kinzhal), an anti-satellite laser (Peresvet), and a hypersonic cruise missile cruise missile (Tsirkon 3M-22). The missions of Avangard, Poseidon, and Burevestnik are to overcome ballistic missile defenses of the American homeland. Kinzhal and Tsirkon are theater weapons, and Tsirkon, depending on the platform, could be used in surprise attacks against the continental US. Peresvet is to be used to blind enemy optical satellites that track road mobile ICBMs. Combined with the already deployed Kalibr Sea-Launched Cruise Missiles and Ground-Launched Cruise Missiles, this new arsenal, when it is deployed, will put a considerable strain on North Atlantic Treaty Organization (NATO) strategic deterrence. While Russia’s objectives are not clear, its military capabilities remain daunting. The Alliance must respond to this challenge. This study examined official Russian publications, open-source press releases, and secondary academic sources, as well as remote interviews with experts in Europe, to assess the challenge posed by Russia and the Alliance’s response to that challenge in 2020. We have concluded that the new developments of the Russian military posture are indeed planned to weaken both the NATO and American strategic deterrent. They are part of a much broader strategic attack on the West across the conflict spectrum, from low-level “hybrid” actions to preparations for regional war.

Keywords: *Russia, NATO, nuclear, precision strike, arms control, military*

Background
Weakening the strategic deterrence capability of NATO and the United States in the European theater was the main strategic goal of the Soviet regime since the end of the Second World War and until the mid-1980s. With gradual deterioration of Russia's relations with NATO countries over the past 15 years, Russia has again returned to a policy of neutralizing NATO deterrence. The various studies of post-Soviet Russia's strategic force policies include: Pavel Podvig, ed., *Russian Strategic Nuclear Forces*; Mikhail Tsypkin, "Russian Politics, Policy-Making and American Missile Defence;" Mikhail Tsypkin, "Russia, America and Missile Defense; "Dmitry Adamsky, *Cross-Domain Coercion: The Current Russian Art of Strategy*; Dave Johnson, *Nuclear Weapons in Russia's Approach to Conflict*, Katarzyna Zysk, "Escalation and Nuclear Weapons in Russia's Military Strategy," Nikolai N. Sokov, "Why Russia calls a limited nuclear strike 'de-escalation;'" Dave Johnson, *Russia's Conventional Precision Strike Capabilities, Regional Crises, and Nuclear Thresholds;* and Kristin Ven Bruusgaard, "Russian Strategic Deterrence," and others. Our task was to build upon such previous studies and investigate the impact of new Russian initiatives in weapons development upon NATO strategic deterrence capability.

NATO recognizes the new challenges that Russia's novel nuclear weapons system poses to Alliance security. However, the Alliance has clearly stated that it will not attempt to mirror every Russian system, and that it has ruled out the deployment of land-based nuclear missiles on European soil. It continues its commitment to a nuclear deterrent that is "safe, secure, and effective," though without providing details as to how it might be improving those characteristics. Presumably, the multiple new studies underway on both the political and military sides of the Alliance are addressing these new concerns posed by Russia's military capabilities. A concerted response will require unity and consensus on the need for firm resolve in the face of new threats. The Alliance continues to support the role and value of arms control as one way of enhancing stability and security, particularly in the face of new military challenges that are not covered by any previous treaty regime.

Findings and Conclusions
This study examined official Russian publications, open-source press releases, and secondary academic sources, as well as remote interviews with experts in Europe, to assess the challenge posed by Russia and the Alliance's response to that challenge in 2020. Our written assessments will provide input to the sponsor organization's considerations of the Russian threat and the US Navy's response. We have concluded that the new developments of the Russian military posture are indeed planned to weaken both the NATO and American strategic deterrent. They are part of a much broader strategic attack on the West across the conflict spectrum, from low-level "hybrid" actions to preparations for regional war.

Of particular importance for NATO are Russian hypersonic missiles, especially the Tsirkon 3M-22, which is in the process of being tested and may begin deployment with the Russian Navy within two years. These missiles have a reputed range between 450 – 1,000 kilometers, and fly at about Mach 8, which would allow the Russian Navy to attack capital ships of NATO members, as well as critical decision-making facilities on land, with limited or no warning. Along with the general slowdown of its economy, the greatest problem Russia likely faces in fielding these new weapons is the weakness of its shipbuilding industry, especially construction of surface combatants capable of blue water operations.

We believe that more than any other great power, Russia continues to pose the most immediate existential threat to Europe and North America. Since at least 2007, it has undertaken a concerted effort to dismantle the treaty-based security architecture in Europe and remake it to President Putin's liking. As a result, Russia has again become a bad actor on the world stage, disrupting the international rules-based system through misbehavior, threats, meddling, and overt military action. In the past decade, it has modernized its entire military, including its strategic nuclear arsenal, and has introduced several troubling new nuclear weapons systems.

Recommendations for Further Research
Future research will be performed as required by the topic sponsor.

NPS-20-N269-A: 21st Century Naval Revolutions

Researcher: Dr. James Russell and Dr. James Wirtz
Student Participation: LT Evan Parrish USN, and LT Robert Putrino USN

Project Summary
The purpose of this study is to better prepare for a potential naval war against America's most dangerous near-peer competitor. The Navy must get ready for this contingency. This research affects all the Navy's principal warfighting communities: surface warfare, aviation, undersea operations, and Special Forces. This study will help the N50 integrate the implications of war in the Indo-Pacific into the Navy's strategy development process.

Naval arms acquisitions throughout the Indo Pacific are being driven by underlying and long-standing political dynamics that show no indication of abating. Arms acquisition patterns will thus continue along to seek a mix of expensive platforms in combination with cheaper anti-access area denial weapons. These digital-age weapons are mostly offensive in nature, which in and of itself creates an escalation instability as political leaders analyze how best to apply their maritime power in pursuit of political strategies that secure their interests.

These acquisition patterns might not be considered threatening if the regional states sought above all to prevent war via deterrence as a strategy to preserve the status quo. As highlighted in this study, however, the principal regional hegemon, China, almost certainly is a revisionist power that seeks to impose its political will on regional rivals through its buildup that features a robust mix of offensive and defensive systems. This asymmetry in motivational framework is inherently unstable and, as argued here, is exacerbated by the nature of the offensive systems entering the arsenals of all parties.

Regional states have a far clearer idea of what a naval battle might look like with their expensive, new hardware but a far less clear idea of how such a battle might fit into a larger war. Like the wars on land, digital-age systems suggest great tactical possibilities that can be misidentified by political leaders as potential strategic solutions. This intellectual and strategic confusion will affect navies' implementation of the political strategies that are the subjects of this study: diplomacy, deterrence, and coercion. The nature of the region-wide naval transformation may in fact undermine political strategies of states that are meant to prevent the outbreak of war or limit the prospects of escalation in maritime-related crises.

Keywords: *change, innovation, maritime strategy, naval strategy*

Background

This project marks the fourth year that the Naval Postgraduate's School of School of International Graduate Studies (SIGS) and its Department of National Security Affairs (NSA) have supported the N3/N5's efforts to better synchronize strategy development with the Navy's plans/programs and policies to develop a fleet that meets the challenges of the 21st century's fluid environment. This study examines the implications of maritime rivalry and war in the Indo-Pacific.

A naval buildup is underway throughout the Indo-Pacific region. Spending could grow by as much as 60 percent over the next five years. The naval buildup reflects complex regional dynamics and bears little resemblance to naval arms races of the early 20th century. Technology is changing the nature and character of a potential war at sea in the Indo-Pacific. The prospects for escalation are far more dangerous than had previously been realized. Crisis management and political decision-making will be more difficult throughout the Indo-Pacific as navies avail themselves of the latest technologies.

Navies are modernizing throughout the Indo-Pacific—a process enabled by growing economies that support steady increases in defense spending that date to the late 1980s. According to the Stockholm International Peace and Research Institute, Asia and Oceana are the only regions of the world that have continuously increased defense spending since 1988. Spending rose by 46 percent between 2009–2018, by far the largest increase of any region in the world. In 2018, the region accounted for $507 billion in defense spending and boasted five of the world's top 15 spenders: China (#2), India (#4), Japan (#9), South Korea (#10), and Australia (#13).

Forecasts of global naval spending highlight the degree to which the Indo-Pacific region constitutes the fastest growing market for naval spending in the world. A 2018 projection by the naval market research firm AMI International predicts that the region will be adding over 1,000 vessels of all types through 2037—more than twice as many as any other region. Of particular significance is that the countries in the Indo-Pacific may purchase as many as 112 new submarines over the period, accounting for more than 30 percent of global forecast. In term of surface combatants, other market data suggest the Indo-Pacific region may spend in excess of $123 billion on new ships through 2027.

Most observers agree that China's military buildup is driving the regional increase in spending on navies. China has identified a series of island chains as important for defense of the Chinese mainland. The most important of these, known as the first island chain, runs from the Japanese islands past the Philippines and around the tip of Southeast Asia. Some analysts suggest that the potential number of island chains spanning the Indo-Pacific will keep increasing in geographic scope as China expands its maritime capabilities.

China's focus on these maritime domains has made them important sources of friction with regional and outside powers. China actively seeks to deny the United States Navy access within the first island chain.

Findings and Conclusions

The purpose of this study is to better prepare for a potential naval war against America's most dangerous near-peer competitor. The Navy must get ready for this contingency. This research affects all the Navy's principal warfighting communities: surface warfare, aviation, undersea operations, and Special Forces. This study will help the N50 integrate the implications of war in the Indo-Pacific into the Navy's strategy development process.

Naval arms acquisitions throughout the Indo Pacific are being driven by underlying and long-standing political dynamics that show no indication of abating. Arms acquisition patterns will thus continue along to seek a mix of expensive platforms in combination with cheaper anti-access area denial weapons. These digital-age weapons are mostly offensive in nature, which in itself creates an escalation instability as political leaders analyze how best to apply their maritime power in pursuit of political strategies that secure their interests.

Recommendations for Further Research

The Navy should continue to deconstruct political, military, and strategic dynamics in the Indo-Pacific, which is likely to be the next theater for a major near-peer conflict.

NPS-20-N271-A: Russian Federation A2AD Posture: Global Impact on USN

Researcher: Dr. Donald Abenheim

Student Participation: No students participated in this research project.

Project Summary

This research interprets the global debate over Russian anti-access and area denial strategy as a threat to the U.S. Navy. Specifically, it underscores how Russia's use of maritime aggression has changed the perception of conflict at sea. The results reveal that the issues at the heart of this study require more resources and greater command emphasis via analysis rooted in properly interpreted Russian sources. Since 2008 and the Georgian war, Putin's Russia has embarked on a campaign of geopolitical revisionism that borrows rather more from its tsarist and Soviet past than certain analysts can easily recognize today. Is this offense/defense a unique, new, and startling innovation? How do allies and partners assess key questions of strategy, operations, combat, and technology? What are the connections of policy/strategy/order of battle as they unfold in the tactical and operational levels as a problem of maritime strategy, and where are the divergences in threat assessment? This study emphasizes the need for U.S. strategists to reacquaint themselves with the fascinating and complex record of Russian strategy over a longer period and to show restraint against being drawn to Washington-centric buzzword summaries of supposed dramatic innovations and revolutions in weapons and military/naval organization. As a result of this study, one should preclude defective theoretical assumptions; reemphasize the fact that these so-called innovations can be seen as a continuation of previously existing strategies, operations, and force structure that reflect Russia's strategic evolution on the level of nation state and military/naval organizations over a century and more. The U.S. Navy must devote greater effort and resources to expertise in Russian maritime forces and how these echelons are used as a tool of policy and aggression.

Keywords: *great power conflict, anti-access and area denial, A2/AD, Russian Federation, Russian maritime strategy, Baltic, Black Sea, Kaliningrad, grey zone conflict, Syria, Caucasus, U.S. Navy, NATO, levels of war, strategy, operations, tactics, fleet posture*

Background

The hypothesis of this study questions whether anti-access/area denial constitutes the danger portrayed by both Russian mass persuasion and in Western threat assessment. Since 2014, the wider strategic implication of Russian strategy for the posture of the U.S. Navy and allied maritime forces has become ensnarled in the grey zone of propaganda verging perilously on escalation to war. This challenge in its 21st-century form is a profound departure from 20th-century attempts to thwart sea control with vessels, aircraft, and weapons closely resembling those of the U.S. Navy and allied fleets. The term "anti-access/area denial" is not limited to specific vessels, aircraft, and weapons of conventional and irregular forces as well as other forms of aggression. Rather, this analysis uses the title "strategic culture," that is, the sum of historical, geographical, state, and even the record of culture of how a state or nation state has comprehended in theory and practice, prepared for, and waged war as well as dealt with its consequences over a long period. While some skeptics damn this term, this research embraces it, not least because it reveals the imponderables of military affairs in greater clarity than solely an operations research inflected assessment of weapons and tactics in abstraction.

The Russian experience of state, society, war, strategy, and the international system of states allows certain generalizations. Russia emerged in the 18th century as a dominant state by armed force and as a European great power. This process included periods of offensives and defenses in relation with the other five great powers with which Russia was often in conflict. This process has fostered the legend, and indeed the myth, within Russia that it is under perpetual assault from all horizons—but especially from the west. Such legend making has justified a strong state at arms on a perpetual basis, especially since 2014. This myth of siege has also rationalized the regime's increasingly bitter attacks on liberalism and pluralism at home and abroad, which is too easily dismissed as simply a "cyber operation" when it is fundamentally more ideological and aggressive. In this regard, the main thrust of Russian statecraft and strategy has been to assure Petersburg/Moscow's dominant role among the European great powers. This goal can be said to have manifested itself with the events of 2008–2014 after a period of real or false entente in the 1980s and 1990. The proof of this generalization is the new civic religion of neo-tsarism, or post-modern Russian nationalism, or neo-Soviet imperialism, all openly verging on fascism. The foundation stone in this dogma stands the brutal victory of the Union of Soviet Socialist Republics against Axis Europe with Nazi Germany in the lead. Added to this 20th century dogma is less well understood nostalgia in Putin's doctrine for the place that Russia held in the Metternich's order in the wake of the defeat of Napoleon from 1815 until the middle of the 19th century.

Findings and Conclusions

This research underscores how Russia's use of maritime weapons, tactics, and strategy quickly change the perception of conflict at sea. The results reveal that the issues at the heart of this study require more resources and greater command emphasis. Since 2008 and the Georgian war, Putin's Russia has embarked on a campaign of geopolitical revisionism that borrows rather more from its tsarist and Soviet past than certain analysts can easily recognize today. This study emphasizes the need for U.S. strategists to reacquaint themselves with the fascinating and complex record of Russian strategy over a longer period and to show restraint against being drawn to Washington-centric buzzword summaries of supposed dramatic innovations and revolutions in weapons and military/naval organization. As a result of this study, these so-called innovations can be seen as a continuation of previously existing strategies, operations, and force structure that reflect Russia's strategic evolution on the level of nation state and military/naval organizations over a century and more.

The principal investigator and his colleagues examined the evolution of Russian and U.S./allied strategy through qualitative policy analysis from high quality strategic research centers and target Russian government, industry, and security studies sectors augmented by historical analysis. The author analyzed contemporary expert debate by an examination of contemporary and past episodes wherein strategy and combat accord with the present threat. Among primary sources, the most significant have been ministerial statements of policy and strategy, the doctrines of the high command, and theoretical military writings, of which there is a long record in Russian and U.S./NATO history. Secondary sources included civil and military scholarship as well as analyses of operations and exercises, which have swiftly grown in number and complexity since 2014.

This study has addressed the misunderstood problem of offense and defense maritime strategy as well as the fundamental strategic and operational character of contemporary conflict centered on Putin's Russia on the march. The results reveal that the strategic community of the U.S. Navy must rebuild its capacity to analyze the strategy, operations, and force structure of the Russian armed and maritime forces. This study will be published in book form in 2021 as part of a large study on great power conflict, weapons, and policy.

Recommendations for Further Research

This research underscores how Russia's use of maritime weapons, tactics, and strategy quickly change the perception of conflict at sea. The results reveal that the issues at the heart of this study require more resources and greater command emphasis. The U.S. Navy should encourage open-source analysis of Russian military developments to counteract Russian propaganda and build the capacity of young U.S. Navy strategists to have the highest familiarity with the Russian military and naval organization. The strategic analysis community of the U.S. Navy must perfect yet more precise and effective methods and processes to sift out propaganda and threat inflation by indirect means. Such research that informs operations and fleet design, especially with so-called grey zone conflict, can move beyond an analysis solely of weapons and tactics. Analysis must include the psychological and political strategic tools of the Russian attempt to thwart U.S. maritime power.

N4 - Fleet Readiness & Logistics

NPS-20-N005-A: New Concepts for In Theater Ship Repair

Researcher: Dr. Simon Veronneau
Student Participation: No students participated in this research project.

Project Summary
This study used a multi-method to conduct a field study of the current ship repair and supply for conflicts against near peer countries such as Russia and China. It built on the PI's current research on supply chain and combat logistics in contested and degraded environments. The overall objective of this study was to evaluate the current shortcomings of ship repair during a major conflict against a peer or near-peer enemy. Findings shows that current vessels in active or reserve status cannot fulfill this mission and that a new class of vessel should be procured. The new concept calls for a fast response vessel based on offshore support vessel design to be able to reach disabled vessels, take them under tow, and offer on-site technical capabilities to fix the system casualty. These vessels could also be paired with accommodation-type offshore platforms that would serve as an offshore sea base outside the conflict zone and allow for greater support capability. Overall, gaining this capability would allow vessels to stay and/or return to the fight without needing to return to a main base in Pearl Harbor or the West Coast.

Keywords: *ship supply and repairs, ship tenders, contested and degraded environments, combat logistics*

Background
Logistical support for U.S. naval forces has not met the test of contested, degraded or denied environments against a serious enemy since WWII. During that war, supply vessels were the primary targets of the German U-boats, which were effective in severely impacting the supply chains that supported the war effort. Recent conflicts were held against enemies with limited ability to disrupt the U.S. Navy's supply chain. Furthermore, recent conflict also posed very few threats to naval assets, as they were not operating in a denied body of waters facing enemy navies. Turning to the decades ahead and the nations of concern to U.S. national security such as China, Russia, and to some extent North Korea, these countries have abilities to deny some environments and target key supply chain enablers. Currently, naval vessels rely on a network of ports in the Continental U.S. (CONUS) and in some key allied nations to conduct the repairs. Given the new threat environment, and the fact that the support of U.S. forces has not been reviewed in decades, this study will look at the current posture, its benefits and challenges, as well as envision a new submarine logistical concept that would be less prone to be degraded by the enemies and would support heightened resiliency. This study builds on our currently funded Naval Research Program work on navy ship supply chain in contested and denied environments, as well as other classified research projects on similar challenges. Given the classified nature of this project and relevant literature, this executive summary is limited.

Findings and Conclusions
This study was based on a field study a using multi-method research approach. An important aspect to this was to travel to key sites both ashore and at sea to see the current ways the Navy is supporting U.S.

forces and evaluate what could be changed and improved. As such, trips were conducted to Pearl Harbor, the San Diego Naval Base, as well as onboard the John P. Murtha. During the visits, meetings and discussions were held with panels of experts, as well as key stakeholders; semi-structured interviews were conducted following the methods of Rubin & Rubin (2005) to obtain insights and explanations. Installations were also visited to assess current capability and shortcoming of U.S. naval repair facilities. A document review of the current inactive fleet vessels was done to assess vessels that would be suitable for the role envisioned available for conversion, e.g., Bremerton, WA. Finally, we met with naval commands to assess the current and forecasted naval forces' needs during phases of conflict. Overall, these efforts are based on a multi-method methodology following key field research methods of Van Maanen (1988). Lastly, while on-site during the operations, opportunistic informal interviews with various workers and stakeholders were carried out, as described in Flick (2008).

The purpose of this study was to identify the current gap in in-theater ship repair, as well as identify possible remediation solutions. This stemmed from concerns at Expeditionary Strike Group III (ESSG III), as well as the Office of the Chief of Naval Operations (OPNAV) N4 that the U.S. Navy lacked the ability to quickly respond and repair ships overseas. We found that there is currently a gap in our ability to respond in or near theater and to provide a quick turnaround to ship casualty in Phase 0-II. This gap cannot be remediated by activating or converting vessels in our inactive fleet or from the current US Merchant fleet. Our findings align with the current community's concerns that the U.S. Navy is lacking a key capability that could best be described as an all-in-one salvage and ship tender that can support the U.S. fleet from phase 0-2 with key technical expertise needed to keep readiness as well as promptly tend to ship system casualties.

Recommendations for Further Research

As neither the U.S. Navy nor its allies currently possess the ability to repair in or near theater, a new fast response in-theater repair capability must be acquired. The commercially available offshore support vessel type would be the best candidate for that function. More specifically, vessels designed for the fast response to offshore oil installation maintenance and repair are well suited for that mission. Designs such as the Damen Shipyard FIRM 120 is especially fitting of the type for the mission's needs. Future research work should investigate the exact cost of the new program acquisition, its sustainment, and the exact design requirements that align with needs for Indo-Pacific Command's (INDOPACOM) and European Command's (EUCOM) potential contingencies.

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NPS-20-N215-A: Applying Big Data Analytics to Improve Naval Aviation Sustainment

Researchers: Dr. Douglas MacKinnon and Dr. Jefferson Huang
Student Participation: ENS Matthew Luerman USN

Project Summary
Our research seeks to improve the U.S. Navy's understanding of its maintenance practices in support of selected critical weapons systems through the holistic analysis of datasets at the organizational level. Our aim is to identify pitfalls in the sustainment of the CH-53E Super Stallion, thus improving aircraft operational availability and improve overall naval aviation effectiveness. Through the utility of data analytics, we examine reported total flight hours, maintenance actions, and percentage of not-in-service equipment, and triangulate these data sets to identify possible root causes or relationships that might affect mission capable (MC) rates.

This exploratory study considers specific categories of data to determine if their use is substantiated and credible. The research sponsor, program office, and other stakeholders may then focus on these particular areas to improve aircraft sustainment and mission readiness. If not, other categories may be recommended for exploration. This can inform a change of approach toward more appropriate lines of effort and potential cost savings for the Department of Defense (DOD).

Keywords: *regression analysis, CH-53E, mission capable rate, sustainment, predictor variables, aircraft maintenance*

Background
The CH-53E replaced the CH-53D Sea Stallion to provide the Marine Corps with a heavy-lift helicopter that is capable of transporting equipment and personnel on rugged terrain during daylight and nighttime operations and inclement weather (U.S. Navy 2019). This combat aircraft allows for the transport of heavy weapons and equipment that cannot be easily accomplished with smaller and lighter rotary wing aircraft and circumstances when use of fixed-wing aircraft may entail greater difficulty to accomplish the mission without a runway or simply a tiny clearance for landing. Additionally, the CH-53E is able to carry greater quantity of supplies and troops at an airspeed of 172 miles per hour and a ceiling around ten thousand feet (U.S. Navy 2019).

The CH-53K King Stallion is the CH-53E's replacement (U.S. Navy 2019). The aircraft is equipped with the latest technology, more power, and a larger capacity. It is already in the test and development phase and is expected to enter its initial operational deployment for the Marine Corps by 2024 (Athey 2019). However, as the CH-53K continues in development until full operability, the CH-53E is planned to remain in operational use through year 2030.The DOD would maintain the aircraft inventory for the entire next decade. An aging aircraft such as the CH-53E has undoubtedly experienced numerous challenges requiring critical attention if it continues to be the primary heavy-lift helicopter for the military.

Findings and Conclusions

A regression analysis suggests that the selected predictors do not possess a causal relationship with aircraft MC rate. One conclusion acknowledges the limited granularity that MC status provides. Given a high count of specific missions that the CH-53E must execute, these aircraft could be deemed MC simply by taking off. Recordkeeping standards about what constitutes an acceptable MC entry may also vary.

The first phase of regression hierarchy testing produced one of three independent variables satisfying a goodness of fit test. Without a second independent variable for multivariate analysis, the second phase – identifying the performance characteristics of combined independent variables to identify our best model – cannot be performed with reliable results. However, the study continued with the testing to demonstrate the unreliability through plotting of regression effects.

Recommendations for Further Research

Other parameters should be explored as the selected predictor variables do not meet goodness-of-fit-criteria. There are other available databases with diverse metrics and focused categories such as cost data, which may open various avenues for further study.

Another suggestion is an extensive investigation of the CH-53E multi-mission capabilities, to attain a more preferable variable set that affects the MC rate. Specific research could be restricted to individual aircraft or by organizational level to analyze a smaller sample of aircraft or squadrons, potentially reducing inconsistencies in MC status entries.

Furthermore, the study explored the most recent three years of data reporting that appeared to identify varied reporting requirements, making comparisons among data sets unwieldy. Therefore, additional exploration and policy adjustment is recommended to make data collection efforts and definitions more standardized and thus minimize reporting discrepancies.

NPS-20-N225-B: NAVEUR Implications of the Current EUCOM's POL Capability & Capacity

Researcher: Dr. Geraldo Ferrer, Mr. Eric Hahn, Mr. Brandon Naylor, and Mr. Lawrence Walzer
Student Participation: No students participated in this research project.

Project Summary

This research focuses on Naval Forces Europe (NAVEUR) implications of current European Command's (EUCOM) petroleum capabilities, and capacities gaps during normal operations through Phase II of its most intensive Operation Plan. The detailed report identified current petroleum demand for Naval operations in EUCOM Area of Responsibility (AOR) from normal operations to Phase II contingency operations and highlighted capability gaps, to include: implementation of limited regional infrastructure, a need for specialized military fuels, and additional requirements for commercial oil tanker support. Specific recommendations include adoption of customized operational fuel safety stock levels, incorporation of innovative refueling capabilities, amendment of existing legislation regarding the use of commercial oil tankers in times of conflict, evaluation of requirements for additional in-theater infrastructure, and expansion of host nation agreements. Our research included the development of a model to identify capability and capacity gaps in petroleum distribution operations during various scenarios of Phase II. Our Naval Postgraduate School (NPS) Fuel Usage Study Extended Demonstration (FUSED) tool provided the means to compare the impact of different policies and practices on the fuel consumption of the surface fleet. Pertinent unclassified conclusions include that future fuel assessments should emphasize the layered operational model, rather than the phased approach, and major commands should consider conducting multi-theater exercises to simulate stressed fuel supply chain. While the preponderance of this study was classified, this Executive Summary provides an overview of our analysis and results. Professional stakeholders in petroleum and distribution operations should consider reading the classified report.

Keywords: *petroleum, oil and lubricants, POL, fuel requirements, petroleum war reserve requirements PWRR, peacetime operating stocks, POS, Phase II, sea lines of communication, SLOC, combat logistics force CLF, Naval Forces Europe, NAVEUR, US European Command, EUCOM, anti-submarine warfare, ASW, defense fuel supply point, DFSP*

Background

The return to Great Power Competition has renewed focus on EUCOM AOR and the potential for conflict. A perennial critical requirement during military operations is the availability of fuel to sustain military forces in standard operations as well as all other phases of conflict. Due to Russian aggression of Ukraine and subsequent annexation of the Crimean Peninsula, and its goal to divide NATO to increase its sphere of influence, NAVEUR must assess its capability and capacity gaps for the supply and distribution of petroleum. This study started by focusing on NAVEUR's supply and distribution of petroleum potential capability and capacity gaps. The primary research question is: What would be the fuel requirements and what would be the potential shortfalls for NAVEUR during Phase II operations?

Two important considerations colored our analysis: Russia has significantly enhanced its military capabilities. In addition, access to bulk petroleum stock at international seaports is not guaranteed. The overarching goal of this study was to identify the resources that might resolve or attenuate such shortfalls. To address the aforementioned research question, we pursued the following research plan: 1. Identify NAVEUR's current petroleum demand; 2. Highlight current NAVEUR petroleum distribution capability gaps; 3. Identify current traits between US Indo-Pacific Command and EUCOM's petroleum capability and capacity gaps; and 4. Recommend resources prioritization.

Please note: Our research team did not have access to reports that were previously conducted by other agencies, reportedly due to proprietary agreements.

Findings and Conclusions

The study included classified fuel data and the Defense Fuel Supply Point lay down supporting NAVEUR operations, to develop the parameters necessary to use the NPS FUSED tool. Our research team developed multiple Phase II scenarios to assess petroleum, oil and lubricants (POL) capabilities and capacities to support and sustain operations. Our research identified several challenges that – when considered in aggregate – highlight the difficulty surrounding fueling the fight in the EUCOM AOR during Phase II of operations. We found that: Phase II of operations would require a very substantial increase in fuel consumption; in the northern part of NAVEUR AOR, the POL infrastructure is limited; Military Sealift Command will require additional commercial shipping for POL delivery to Defense Fuel Supply Ports.

Considering those challenges, our analysis led to several recommendations. In the short term, the following actions should be taken: 1. Customize operational fuel stock levels to reduce the need for refueling operations; 2. Increase operational reach and tempo by adopting innovative refueling capabilities; and 3. Amend existing laws to enable leveraging foreign-flagged commercial shipping support for POL delivery. In addition, in the long term, it will be necessary to consider expanding fuel infrastructure in the NAVEUR's northern area of operations, and to further leverage host nation and commercial capabilities.

All findings are provided in greater detail in the classified report.

Recommendations for Further Research

This concern with petroleum, oil and lubricants (POL) distribution in US European Command (EUCOM) would benefit from further studies of the following topics: the analysis of fuel supply distribution to enhance the operational reach and sustainment of anti-submarine warfare (ASW) operations, and the distribution capabilities and capacity challenges of Jet Propellant #5 (JP-5) to support air and naval operations.

NPS-20-N247-A: Optimal Pre-Positioning of Bulk Fuel Resources

Researchers: Dr. Jefferson Huang, Dr. Moshe Kress, and Dr. Michael Atkinson
Student Participation: Maj Steven Kasdan USMC and LCDR Christopher Norman USN

Project Summary

In response to changes in the global threat environment, the U.S. Navy (USN) and U.S. Marine Corps are currently shifting towards distributed maritime operations (DMO) and expeditionary advanced base operations (EABO). This has motivated the development of new fuel distribution concepts for providing in-theater support to spatially dispersed forces. One such concept involves the use of low-signature, mobile, and potentially unmanned storage systems to dynamically preposition fuel amid evolving threat conditions. As part of initial efforts to assess how this concept can potentially be integrated into the USN’s fuel distribution network, we formulate optimization models that can inform how such storage systems should be located, and how their capacity should be allocated. Case studies based on notional conflict scenarios are used to illustrate data requirements, and to numerically assess the sensitivity of model outputs to input parameters. The models are intended to serve as a foundation for how disaggregate fuel capacity should be allocated and are flexible enough to be adapted to account for specific features of the storage system concepts (e.g., fuel capacity, speed) as they are developed.

Keywords: *distribution, energy, fuel, logistics, prepositioning*

Background
Motivated by changes in the global threat environment, the Chief of Naval Operations (Gilday, 2019) and the 38th Commandant of the Marine Corps (U.S. Marine Corps, 2019) call for operational concepts, such as DMO and EABO, that will require innovative logistics concepts to support distributed forces over large contested areas (Walton et al., 2019). One fuel distribution concept that has been proposed for integration into the USN's supply network is the use of low-signature, mobile, and potentially unmanned bulk fuel storage systems (Walton et al., 2019), henceforth referred to as bulk fuel caches (BFCs). The successful integration of such a concept will require methods for determining where BFCs should be pre-positioned, when and where they should be re-positioned under evolving threat conditions, and how fuel capacity should be allocated. In this project, we view these planning problems from the perspective of location analysis, which is a well-studied sub-field of operations research with numerous military applications (Bell & Griffis, 2015).

Findings and Conclusions
The primary contributions of this study are (1) a basic discrete optimization model for locating BFCs and allocating their capacity, and (2) new continuous optimization models for routing one or more mobile storage systems. The first contribution (Kasdan, 2020) consists of formulating the location and capacity allocation problem as a so-called p-median problem (ReVelle & Swain, 1970) that accounts for constraints on BFC capacities. In this formulation, there are a finite number of possible BFC locations, which may be interpreted as regions that can potentially be assigned a BFC. Location and allocation prescriptions are obtained for notional conflict scenarios set in the South China Sea and indicate the potential benefits of additional capacity. For instance, up to seventeen percent gains in performance were observed for increases of less than eight percent in capacity (Kasdan, 2020).

While the outputs of the capacitated p-median model referenced above were evaluated over multiple periods, the model itself does not explicitly determine how the potentially mobile fuel storage units should be re-positioned over time. The second contribution addresses this via the formulation of a dynamic facility location model (Wesolowsky, 1973) that determines the optimal routes for one or more BFCs, given the operating plan of the units they will be supporting. In this formulation, the decision variables consist of the coordinates of each BFC at the start of each planning period, and in the multi-BFC formulation also include the allocation of BFC capacities to the supported units. Notional operating plans are used to illustrate the kinds of outputs that our routing and allocation model can produce.

Recommendations for Further Research
This project addresses the basic problem of how a given inventory of low-signature, mobile, and potentially unmanned bulk fuel caches (BFCs) should be positioned, and possibly re-positioned, in order to efficiently and effectively serve the fuel needs of supported units. Given the foundational models for this purpose that have been developed in this project, there are two primary directions for further research in support of a fuller assessment of how BFCs can potentially be integrated into the U.S. Navy's fuel distribution network, while also supporting the needs of the U.S. Marine Corps. The first direction is the incorporation of more realism into the models formulated in this project, in a way that effectively trades off model complexity with efficient solvability. Aspects to explore include replenishment policies for the BFCs themselves, accounting for BFC attrition explicitly, and the incorporation of relevant features of actual/planned implementations of the BFC concept. The second direction is the inclusion of potential

interactions between the BFCs and other elements of the fuel supply network, such as Combat Logistics Force ships. More generally, the line of work described here can potentially be applicable to other contexts where resources can be dynamically re-positioned.

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NPS-20-N250-A: Sustaining our Submarine Forces for Phase 0 and Phase II in a Contested Environment Against Peer and Near Peer Countries

Researcher: Simon Veronneau

Student Participation: No students participated in this research project.

Project Summary

This study used a multi-method approach to conduct a field study of the current submarine repair and supply posture for phase 0 to phase II against near peer countries such as Russia and China. It built on the researcher's prior work on supply chain and logistics in contested and degraded environments. The overall objective of this study was to evaluate the current shortcomings of submarine logistics during Phase 0-II against a peer or near peer enemies as well as how can we maintain an effective and efficient posture for outside the continental U.S. support of our subsurface forces, and also envisioning what should the logistical support of our submarine forces look like in the decades going forward. Travel to key sites was conducted in order to gather information on the various requirements and current challenges as well as understanding the commander's intent. Review of archival data and current key plans was done to understand the context of this study. Current ship and submarine repair capability is already limited and running at full capacity. Findings show that the U.S. Navy needs a renewed focus on having a skilled and available technical workforce that can be geographically nimble and ready to surge in capacity. Having a combination of a robust network of both sea and shore-based support would be the best way to position

the U.S. Navy to prevent the conflicts of tomorrow. The two key elements of this geographically nimble presence requires both an increase in personnel and platforms to project the personnel and capabilities both in the air and at sea.

Keywords: *naval forces sustainment, combat logistics, submarine sustainment, submarine tenders, contested and degraded environments*

Background

Logistical support of our naval forces has not met the test of a contested, degraded or denied environment against a serious enemy since WWII. During that war, supply vessels were the prime targets of the German U-boats, which were effective in severely impacting the supply chains that supported the war effort. Despite the U-Boats success, the American industrial base and superior ability to project supply chains globally made the difference in curbing and defeating both German and Japanese forces. Recent conflicts were held against enemies with limited ability to disrupt the U.S. Navy's supply chain and no recent enemies in conflict have had the capability to cause severe strategic disruption and casualties to our naval forces. Turning to the decades ahead and the nations of concern to our national security such as China, Russia, and to some extent North Korea, these countries have abilities to deny some environments and target key supply chain enablers through regular warfare, irregular tactics as well as some cyber and cyber-kinetic capabilities. Currently the U.S. submarines rely on a network of ports, as well as submarine tenders to offer repairs and resupply at sea. Given the new threat environment and the fact that the support of our submarine forces has not been reviewed in decades, this study looked at the current posture, its benefits and challenges, as well as envisioned how to improve our logistical posture in order for our support functions to be less prone to be degraded by the enemies, as well as provide heightened resiliency. This study builds on the researcher's previous work on strategic supply chains in contested and denied environments as well as other classified research projects on similar challenges. It aims to guide some of the future funding priority in order to provide an efficient and effective support posture to our forces.

Findings and Conclusions

This study aimed to answer important key questions that OPNAV N421 Combat Logistics Questions had on the support of our submarine forces in Phase 0-II. The combat logistics function has been getting renewed interest as we realize that the fight of tomorrow will be against enemies of greater might with the ability to strategically disrupt the support of our forces. While the problem of a contested and denied environment has been getting more attention, the problem of how to best sustain our naval and sub-sea forces against peer enemies is still not fully revisited to the reality of this century. To do so, a field study using a mixed-method approach was chosen. Field trips were conducted to see a re-armament evolution in Norway and repair and re-supply operations in Kings Bay, Georgia, and Pearl Harbor, Hawaii. The commander's intent and plan were assessed and discussed while visiting Commander Submarine Force United States Atlantic Fleet (COMSUBLANT) and Commander Submarine Force United States Pacific Fleet (COMSUBPAC). The COVID19 crisis made some of the original trips impossible to conduct and some key exercises to observe were cancelled. The final report is based on a multi-method methodology following key field research methods of Van Maanen (1988); on-site during the operations, the methods of Rubin & Rubin (2005) were followed: semi-structured interviews were conducted with key stakeholders to obtain insights and explanations on technology and processes. Lastly, informal interviews with stakeholders were carried out when opportunities arose on an ad-hoc basis, as described in Flick (2008).

One important question for this research was to evaluate if a shore-side approach or a tender approach to submarine sustainment was a better approach. This study found that aside from the actual transportation and maintenance assets required for both types of support, future concepts need to focus on the personnel providing the support and allow a surge of capacity as opposed to a transfer of capacity. In many situations, the best approach would be to have a combination of approaches to solve a problem; hence, in this case, the better approach is to have both a shoreside forward deployed presence and nimble sea-based facilities like tenders or offshore sea bases. One key observation during the field trip was that some of the submarine sustainment and operational processes lack a key performance requirement such as an acceptable reload time for weapons or repair time for a system. The lack of such standard requirements yields systems and processes that do not have any guidance or timeline for key activities. This then translates to a new design for submarines that do not have as a guidance nor a priority to focus on key issues such as acceptable cycle time for torpedo reloads. Lastly, the geography of the U.S. Navy support network needs to be re-evaluated for the new threat vectors from growing capabilities from our potential adversaries. Places that were once deemed safe sanctuaries to conduct repair and sustainment of our forces are no longer immune to serious adversarial attack and disruptions.

Recommendations for Further Research

Future work should look at queuing theory to determine the capacity needed to successfully maintain the current force within the planned maintenance availability period as well as slack capacity needed to meet a surge demand in capacity. The queuing research should also consider commanders' intent and what is an acceptable likelihood of delay that would be acceptable in Phase 0 through Phase II. An in-depth process review should also be conducted for all key steps of the sustainment process in order to find process re-engineering opportunities as well as vulnerabilities to failure.

One important element still missing for successful operations is guidance on the desired cycle time for many processes. Currently, the doctrine is not to set time goals in order to keep a safe operation. Hence, as an example, there is no formal guidance on the length of a torpedo reload evolution to prevent a rush in operation that could cause accidents. Other areas of sustainment lack these clear benchmarks due to either safety or a lack of awareness of this issue. Setting desired cycle and performance requirements considering sustainment is important for both an operational excellence element as well as a system design perspective. If engineers are not given a goal to have a fast, safe, and efficient weapon reload process and a clear goal of a certain number of hours, it will not translate into systems that will be compatible with the commander's intent of adequate rotation in and out of battle.

Lastly, more research should look at the problem of the capacity needed for a surge with specific attention to defining a workforce that has slack capacity in reserve for contingencies operations. This could take many forms like military reservist or even perhaps time for a technical reserve force that have the right skill set required in a contingency as well as familiarity with the various military systems.

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NPS-20-N290-B: Navy Additive Manufacturing Afloat Capability Analysis

Researchers: Dr. Douglas Van Bossuyt and Dr. Amela Sadagic
Student Participation: Nathan Banks CIV, Daniel Ferreira CIV, Jerome Mccauley CIV, Joseph Trinh CIV, and Kenneth Zust CIV

Project Summary
In 2014, the Department of the Navy (DoN) began installing additive manufacturing (AM) capabilities aboard surface vessels. The DoN is expected to accelerate fleet integration of AM over the next decade. In terms of logistics and operational readiness, this research aims to aid decision makers in understanding how to optimize the deployment of AM resources to the Navy's Surface Fleet. AM systems were analyzed for capabilities including material options, build volume, operating environment, printed part certification, and quality. The research identified existing DoN AM equipment and forecast near-term future AM acquisitions. The research has also identified logistics and support requirements for AM equipment; examples include feedstock type, spare parts, supportability, maintainability, and usability. The results of this project include a pilot demonstration software product, which may be used by the Navy to facilitate the integration of AM on surface vessels, as well as a systems engineering methodology to maximize AM benefit across the fleet.

Keywords: *additive manufacturing, AM, 3D printing, repair, maintenance, fabrication, production, manufacturing, prototyping, rapid prototyping*

Background
Although the Navy fleet currently has AM capabilities onboard several vessels where training, experiments, and best practices are being explored to take advantage of AM technology to increase fleet readiness and lethality, the Navy desires to expand the number of AM machines on vessels under sail. Although increased fleet readiness is the primary objective of the Navy, a preliminary study has shown that AM can result in cost savings when acquiring obsolete and long-lead components (Nicholls, Han, & Davis, 2019). The vessels that are best suited for AM integrations include aircraft carriers and amphibious warfare ships, but benefit is also anticipated for installations on cruisers, destroyers, and other surface warfare ships.

The American Society for Testing and Materials (ASTM) group defined and designated seven categories of AM technologies (ASTM International 2012). The seven categories are: Vat Photopolymerization, Powder Bed Fusion, Binder Jetting, Material Jetting, Sheet Lamination, Material Extrusion, and Direct Energy Deposition. Each of these categories has distinct part production capabilities and limitations. In addition, there is a broad spectrum of raw materials available for AM, ranging from polymers to metals. Generally, AM machines are designed to utilize certain raw materials, and laboratories need multiple machines to support a full range of production capabilities. Also, AM equipment can have their performance and part quality degraded by the machine's operating environment, including humidity, vibration, shock, and fluctuations in the power supply. As such, environmental factors are prevalent on Navy vessels, so there is a need to incorporate environmental controls to optimize performance under adverse operating conditions.

Therefore, environmental conditions must be managed in the spaces that AM machines are located, and the Navy may need to consider creating spaces specially for AM. Vessels may also have to modify their concept of operations when operating certain AM machines, given that some AM raw materials, and AM equipment pose hazards to personnel and to the vessel itself. For example, powdered metals can react with other materials onboard, resulting in toxic fumes, fire and explosions. As a result, AM machines currently in use on naval vessels have low material outgassing and are safe to store and use in enclosed spaces. Material, process, and environmental controls are a very important consideration as certain raw materials are toxic and can be flammable or explosive while being stored or used. The intended locations of these AM machines will be within the confines of the naval vessels that have limitations on air filtration and ventilation capacities, which, if exceeded, would create a health hazard to the crew. Therefore, it is critical to understand the quantity of AM machines that can operate without overwhelming ventilation, along with other resource limitations.

Findings and Conclusions

This project focused on three primary research questions:

1. Identify types of AM equipment that can best serve the needs of the Navy's surface fleet
2. Propose a method to determine the optimal AM deployment order across the fleet
3. Present an advantageous dispersion plan to maximize the benefit for the surface fleet

The first research question was addressed by building the pilot demonstration software product, which provides the rankings for the AM equipment to best serve the Navy's surface fleet. However, this software tool is only as effective as the inputs it receives from the users, and should be periodically reviewed and updated. It does provide a structured method using Multi-Attribute Utility Theory processes to analyze the individual AM equipment quantitatively. The software should be part of a recursive process with the inputs updated as new technologies are introduced, and as users gain more experience using the deployed AM systems, and as new requirements are defined. The AM equipment rankings provided in the AM Equipment Dispersion Plan Analysis Result are relative only to those listed in that report. Any changes to the software inputs would affect the outcome in the software report and that, in turn, would improve the utility for future deployments.

The second research question was addressed by creating a vessel scoring matrix to determine AM deployment priority, which provides a method for organizing, scoring, and ranking the Navy's surface fleet. This methodology includes scores for both a vessel's need and ability to utilize AM equipment and technologies, concluding that larger ships will have both higher need for AM as well as increased ability to utilize AM. This methodology proposes that the Nimitz and Ford-class Aircraft Carriers, as well as the America-class Amphibious Assault Ship, should be the Navy's highest priority for AM deployment. These large vessels have both the laboratory space to install AM equipment as well as the personnel to utilize the equipment successfully. The Navy must balance the scores and rankings provided in this study with each ships' availability periods to determine actual deployment order throughout the fleet.

The third research question was addressed by creating a fleet dispersion plan, which provides a three-phased approach to AM integration across the surface fleet. Each phase can utilize the software product to elicit preferences from the sponsor or decision-maker regarding AM equipment type. Once the equipment is selected, it will be deployed to the vessel in accordance with the functional flow proposed in the fleet dispersion plan. After the users have been trained and the equipment is operational, feedback must be provided back to the software product to make necessary updates, and to the ship's sponsor and decision-makers, to assist them in creating and improving future integration phases. As AM gets integrated onto surface vessels across the fleet, the feedback loops will amplify benefit for subsequent installations, creating additional value and motivation for forthcoming installations. The use of the software product, the vessel selection method, and the fleet dispersion plan work together to maximize AM benefit across the fleet.

Recommendations for Further Research

The process of creating an optimal additive manufacturing (AM) implementation plan for the Navy is built on the foundation of understanding the needs of the stakeholders, while simultaneously assessing the capability of AM technology itself. Regarding future work in this field, it is recommended that the Navy study and modify software product such that the embedded AM machines library is kept up to date. Even though AM machine research was performed, and stakeholder analysis conducted, which resulted in the current list of AM machines contained within the software, it is very likely this list will become obsolete in a short period of time due to rapid technological advancement. As a result, we recommend that the Navy allocate resources to maintain the software so that it contains AM machines on the leading-edge of AM technology and capability.

We also recommend deployment of a database containing a library of parts and assemblies to support afloat AM parts and on-demand production. Likewise, the Navy should work to incentivize contractors and suppliers to utilize design for additive manufacturing (DfAM) for a significant portion of their produced components. The Navy's goal of obtaining high efficiency, high performance AM technology is achievable by applying systems engineering methodologies and practices to construct a multifaceted system design and implementation plan. Notably, over the past several years, AM technology has seen rapid technological progression, which will continue. Therefore, the Navy should perform continuous assessments on AM equipment and technologies; regarding future AM equipment and technology acquisition, the suitability, usability, and supportability for operations onboard a naval vessel must be addressed.

Further, if the Navy limits future work by simply focusing or remaining within the scope of this project, the full potential of AM technology and its application will not be realized. The key to success regarding the future of AM technology and its integration in the naval domain is to begin treating and procuring AM systems and technology using a system of systems approach. For the AM system of the future to reach its maximum potential, it will require a high level of interoperability and integration with many naval systems. As AM use, integration, and interoperability increases within the Navy, the operational availability of other systems, as well as fleet readiness, will likely increase.

Additionally, it is recommended that the Navy conduct research to determine if and where AM technology can be applied in support of other military branches and other mission types, whether supporting sea or land assets. Recently, the Navy has been involved with supporting natural disaster relief for earthquakes, tsunamis, and hurricanes, all of which can destroy infrastructure, including supply chains, which are needed to bring in replacement parts to restore power and water supplies.

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NPS-20-N362-A: Blockchain Technology in Support of Navy Logistics and Global Supply Chains

Researchers: Mr. Walter Kendall and Mr. Arijit Das

Student Participation: LT Carlos Correa BRA, LT Phillipe Tavares Alves de Siqueira FORNATL BRA, Avantika Ghosh INT, and Aroshi Ghosh INT

Project Summary

Navy logistics supporting forces at sea is a complex process involving the procurement and transportation of material and its payment and tracking. Naval logistics involves diverse parties, including some outside of the Navy. For food and parts, issues of provenance and authentication of transactions are important to the logistics process, which are the major features of blockchain. Blockchain is a trusted distributed ledger that can record transactions including financial, facilitate even payment, and provide trust and security for these transactions. Blockchain uses a concept called smart contracts that can embed legal knowledge, laws, and regulations to enforce Navy logistics policy or catch errors in transactions. Blockchain can reduce friction in the logistics network by lowering cost and creating a faster and more agile process. Our methodology is based on three basic use cases provided by the sponsor: 1) financial and inventory transaction audit trails; 2) serial number tracking; and 3) maintenance log integrity.

We identified Hyperledger Fabric as the most promising technology that maps well to the three general use cases. We compared the IBM and Oracle Blockchain platforms with its ability to support the three use cases. Any implementation of an enterprise blockchain must consider the whole network infrastructure and its ability to connect to the last mile to legacy Navy systems. We implemented a simple demonstration blockchain network on both IBM and Oracle platforms to illustrate the ability of blockchain to track, validate, and enforce business rules through smart contracts. This capability would be needed for any of the three use cases, which are sometimes done manually or not at all.

Keywords: *logistics, supply, supply chain, workflow, blockchain*

Background

Blockchain is a tamper-resistant decentralized database used in many security applications to provide proof of transaction where trust is implemented through distributed consensus and not centralized policy enforcement. Blockchain is a distributed ledger where all approved users have a copy, and the ledger can be trusted. This trusted ledger can record transactions, including financial, and can facilitate the payment process. Smart contracts can embed legal knowledge, laws, and regulations, and enforce Navy logistics policy. Blockchain can also provide "provenance" of an item such as food or a part and trace back to the source of that part or food item in case of contamination or counterfeit/defective parts. Blockchain can be used for cyber currency such as bitcoin; cyber currency is not a part of this study, although it offers in the future another way to conduct financial transactions.

The blockchain concept is represented by such technologies as Hyperledger, Everledger, and Ethereum. Such technologies could be used in Navy supply and logistics to streamline and improve effectiveness in terms of how workflow can be improved to provide more rapid and secure distribution of material and two-way financial transactions. Logistics performance is reduced by administrative friction, which can be caused by audit requirements, trust issues from generated financial transactions, and other admin processes.

This research asked, could blockchain simplify and enable access and identity management for the Navy supply and logistics systems in a cost-effective manner to reduce this friction? How could blockchain improve Navy logistics to the last tactical mile? In addition, we answered the specific questions below:

1. What are the potential benefits/costs of blockchain and related technology for the Navy logistics and supply business transactions?
2. What type of blockchain technology and general architecture would best meet the Navy's logistics/audit requirements that meet both security and other requirements?
3. How can blockchain technology reduce data entry errors in Navy business transactions? Would a "consortium blockchain" be the model for the Navy to adopt in its logistics system?
4. How could blockchain add capability to Navy logistics and supply?

Findings and Conclusions

Blockchain technologies offer the potential to reduce costs and logistical friction by providing a trusted ledger in support of logistic transactions and processes. Errors can be reduced through smart contracts as demonstrated in both IBM and Oracle Blockchain platforms.

We used a qualitative methodology that included three general logistic use cases: 1) financial and inventory transaction audit trails; 2) serial number tracking; and 3) maintenance log integrity. These were used in consultation with the topic sponsor. We created simple scenarios where items were tracked through a blockchain network and smart contracts would check for certain conditions that would simulate quality control and tracking. We selected two enterprise Hyperledger Fabric platforms, Oracle and IBM, and evaluated in terms of functionality, development ease, and security.

We found that both IBM and Oracle Blockchain platforms may be used to create a secure network of peer nodes or naval hotspots that can generate a consensus for the legitimacy of the shipment ledger, which can only be modified using smart contracts. Since a key component of both platforms is maintaining accuracy and security of the ledger; all users must consistently export and import the smart contracts and ledgers onto their respective peer nodes every time an update is made on the ledger or if the transaction protocol on the smart contract is changed. A special concern with Navy logistics is the possibility of unreliable networks, especially from shore to ship. The blockchain protocol creates a multitude of copies of the blocks (the public ledger) and if connectivity is lost, the blocks will be updated once the network node communications are reestablished. Both IBM and Oracle blockchain platforms were accessed through the cloud, but the option is for the Navy to put either platform on its implementation of the cloud or on servers.

There were differences between IBM and Oracle implementation of Hyperledger Fabric such as how the whole network infrastructure was implemented, user interfaces, the developer tools and application programming interfaces provided, and how the implementation would connect to the Navy's legacy systems to reach the "last mile" such as on the ship. These were real value-added capabilities, since Hyperledger Fabric alone cannot make an enterprise blockchain system that supports the existing logistics information system.

We found a "consortium blockchain" with a blockchain consensus network the best fit for the use cases. A consortium allows both private and public users to use the blockchain while control is maintained by the private users (the Navy) through a consensus network, which means by the consensus of trusted Navy entities. This is contrasted by "proof of work" blockchain networks used in cyber currency, which are inefficient and not appropriate for a government entity.

Blockchain technology has the potential for revolutionizing the logistics process by ensuring the quality and trustworthiness of logistical generated data as well as providing provenance of parts and food, but it is new and risky.

Recommendations for Further Research

Our recommendation is to look at small pilot projects using permissioned enterprise blockchain to demonstrate the usefulness of it to improve aspects of the surface Navy supply chain such as its use for the tracking of non-aviation parts, and food, including food safety. Another blockchain use is for maintenance log integrity. Maintenance logs are generated through maintenance transactions, but often some data is wrong or not updated, which can impact mission readiness or understanding of the true situation. When that data is extracted for analysis, there could be so many errors that impact statistical analysis, thus preventing an understanding that would lead to better decision making. Also, since blockchain is in essence a database, it could be used as a source for almost real-time analytics since the blockchain is never overwritten.

There have been previous pilot studies including a Naval Air Systems Command blockchain prototype to track and manage aviation parts (Kenyon, 2019) and a similar Air Force effort (*Ledger Insights*, 2020), but the suggested pilot projects would explore other uses for this technology besides the tracking of aviation parts.

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NPS-20-N362-B: Reconditioning Blockchain to Enable Global Supply Chain Assurance

Researchers: Dr. Britta Hale, Dr. Donald Brutzman, and Mr. Terry Norbraten
Student Participation: LCDR Jonathan Culbert USN

Project Summary
Distributed ledger technology, such as blockchain, could ideally be used to solve challenges in global supply chain assurance. In blockchain, consensus is achieved among active concurrent participants. The chain is, by design, required to be a single forward-building path of events; if branches appear, the chain consensus ensures that all but one branch is discarded. A supply chain in comparison, particularly on the production side, is a reversed architecture. In this case, small parts are used to build larger parts, hence requiring chain mergence (e.g., a final ready-for-use vehicle is comprised of multiple smaller parts sourced from various vendors, manufacturers, and even countries). Thus, the current capabilities of blockchain do not meet the fundamental demands of supply chains. Assuring supply chain integrity and visibility requires an adaptation of blockchain to allow a form of mergence that the original concept was not designed to handle.

This research looks at a possible solution among hash chains, blockchain, and ledger options for supply chain strategy. To that effect, we survey existing blockchain solutions for forms of mergence, i.e., solutions for merging chains into a single blockchain, such as would be necessary for supply chain assurance. We analyze potential solutions using partner signatures (where supply chain partners commit to chain addenda by digitally signing new blocks while also committing to the entire previous chain). This requires analysis of security considerations based on different commitment variants. Furthermore, it requires consideration of potential timelines and timeline collisions of block production. The above solutions are evaluated with respect to formal blockchain integration. In particular, the research investigates whether or not merging of distributed ledgers is possible within exiting blockchain architectures, or if it is feasible as a parallel assurance mechanism, such that commitments are uploaded to an existing blockchain. This evaluation will be made on mathematically feasibility as well as use case comparison.

Keywords: *supply, blockchain, Distributed Ledger Technology (DLT), Hyperledger Fabric (HLF), Supply Chain Management (SCM)*

Background
Since its inception under Bitcoin and cybercurrency, blockchain technology has often been touted as a solution to various challenges; however, blockchain technology may also benefit Navy logistics. In essence, blockchains are a list of records, or blocks, cryptographically linked as a distributed ledger for recording transactions among parties in a permanent and verifiable way (Zheng et al., 2017). Blockchain could also support "smart contracts" which may be away to reduce administrative friction.

The hallmarks of a robust Distributed Ledger Technology (DLT) are decentralization between blockchain networks and the individual nodes in those networks, as well as the consensus reached when validating individual blocks when added to a network's blockchain ledger (Khan, 2019). Khan (2019) also notes that characteristics such as the number of transactions per second (TPS) that a network can process, the network's scalability and how a particular network guards against malicious attempts to add false information are also key to a good system.

This work focuses on authentication of changes at the micro-level with transparency in a ledger for support of supply chain assurance. Industry is working on several efforts involving supply chain logistics and supply chain management such as Hyperledger (2020), Everledger (2020), and Ethereum (2020) that may have an application to the Navy's logistical systems, and perhaps could contribute to an agile logistical system. The central challenge is applying such efforts beyond acquisitions to the whole lifecycle of the supply chain.

Findings and Conclusions

Littoral Combat Ships (LCS) have two classes of relatively small surface warships designed for operations near shore by the U.S. Navy ("Littoral combat ship," 2020). Reduced crew complements mean individuals are assigned, yet with reduced inventories of spare parts and supplies. The use of unmanned aerial vehicles (UAVs) often helps in this regard. The ecosystem for a typical UAV consists of four categories of components, including, hardware: airframe, sensors, computers; software: communication, guidance and control; Additive Manufacturing (AM): 3D printed wings, tails and other small parts for ad hoc repair; and information: keys, training, repair instructions, feedback and safety.

Within these four categories of components, each is different and necessary for aggregation into a complete device, as each has different stakeholders and supply chains feeding ships' supplies. Thus, four parallel supply chains of interest exist, and each is interdependent. Any mergence solution should necessarily support all four aspects. Note that even with acquisition of a device as a single unit, the nature of updates, potential repairs, and parts reuse between devices imply that for tracking purposes, over the device lifetime, it must be possible to handle the merging of all four aspects.

Suppose that a ship deploys with stock gear and consists of two distinct, yet similar versions of a UAV. Under normal operations, the following issues may affect device history, in that they impact the integrity of the device or its trustworthiness, and therefore should be added in an authenticated manner to the device history: software updates, training and safety updated to ship standard operating procedures and tactics, training and procedures. Now suppose that a collision occurs during testing between the two UAV causing damage to each vehicle. The following may also be important changes to the device history, requiring authenticated changes in device records: hardware replacements on board, to include classified components; 3D printing for upgraded tail assemblies; or maintenance of feedback to shore commands. Any mergence solution must therefore support, per minimum such a variety of changes to the item history.

There are also requirements in how a change is recorded. In terms of verifiability, the following requirements are also essential and must be supported by a mergence solution: conformation that a given component X is on the ship; conformation of all devices in the inventory that have X as a component; conformation if and when X has been replace/repaired/etc., within a particular device; conformation of the change entity, i.e., the responsible party to change/split/remove/combine X as a component within devices; ability to add logs or metadata.

Likewise, if a device component is found to be compromised and must be removed, the logged data associated with the device should indicate if it has been removed and by whom. Furthermore, is it important for administration purposes to identify all possible devices containing the compromised component for swift handling and damage mitigation.

Finally, we list flexibility requirements associated with mergence. Since mergence solutions must support potential external (industry/non-Department of Defense [DoD]) supply chain tracking of unpredictable natures, the mergence solution must be adaptable.

There is a natural separation between external-Department of Defense (DoD) and internal-DoD supply chain tracking. Even for internal supply chain tracking, satisfying all solution requirements appears, on the outset, to be impossible. Notably a solution that crosses classification boundaries must be carefully handled, especially for full item records and tracking information. We handle this by further separating out the internal DoD authentication chain into two parts.

DoD equipment is typically procured via outside commercial manufacturing vendors. The supply chain starts outside of the DoD, where parts and other equipment must be verified and validated before becoming available inside internal supply chains. Conceptually, manufacturers many require supply chain assurance as well, tracking purchased components for integration in building devices. This may take the form of various blockchains. Minimally, manufacturers may be required to present verification on the types and sources of a device's components. At acquisition, a new item record will be formed, such that the component history of the acquired device is verified and authenticated by the acquisition authority, who registers components under a digitally signed genesis block. Once a genesis block for the internal ledger is formed, tracking may proceed internally.

What is essential at the DoD boundary/component registration step is the actual verification of internal components to a device, that is, information on processing chips, software, extra must be recorded. This enables future tracking such that if, for instance, a component is later discovered to be compromised in the manufacturing chain, all devices containing the critical component can be identified. The genesis block thus serves as an initial registration for all components, such that it is only necessary to record changes to that initial list within the device history record.

We break internal tracking into two further chains, to support classification boundaries. The *device chain* handles immediate time history, and authenticates records as visible to the admin. Moreover, the device chain is designed to support the current Depot Level Repairable system. Within the mergence solution, we also support one or more internal blockchains in addition to the device chain. Here, we employ the term blockchain for a distributed immutable ledger, without specification that restricts to any ledger format or consensus method. For hybrid devices used in the fleet, activities may occur and be needed across multiple levels and domains of security, such as UNCLASS, CONFIDENTIAL, SECRET, and TOP SECRET. For this we map our solution to the Multilevel Security classification system and demonstrate interoperability.

Note that while the device chain contains potentially classified information, the information sent to the blockchain is comprised of merely the signature on the data vs. the data itself. Any further additions are optional. Even with a time code associated to the signature object representation there is no intrinsic value to the information outside of the context of the signed data, especially with a plentitude of blockchain transactions. Thus, the blockchain information can be shared across multi-level security systems since these codes are useless without ledger/database access.

Recommendations for Further Research

We recommend a formal analysis of the mergence solution and expanded testing for deployment viability. While Hyperledger Fabric was used a testing conduit, other underlying blockchain platforms may prove to be useful in practice.

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N8 - Integration of Capabilities & Resources

NPS-20-N033-A: Network Traffic Covert Channel Detection and Mitigation

Researchers: Dr. John Monaco and Dr. Gurminder Singh

Student Participation: PO1 Jeana Verkempinck USN, PO1 Alexander Arnell USN, and CPO Cassondra Bullock USN

Project Summary

Instant Message (IM) applications are commonly used by both civilian and DoD personnel for both communication and collaboration. The web-based variants of these applications generally ride encrypted channels for message security. However, these channels may be vulnerable to keystroke timing attacks whereby textual content is determined by the timing of network traffic induced by keyboard events. An example of this induced traffic is the activity notifications common to many of these platforms, indicating when a conversant begins typing. Our aim is to determine whether the network traffic that carries this metadata enables recovering portions of the message or leaks information about the sender's identity. Using a combination of network traffic analysis and keystroke logging, we characterize the traffic patterns of three widely used web-based IM platforms: Facebook Messaging, Google Hangouts, and IRC through the Kiwi IRC web client. Comparing the packet timings to keyboard event timings on the host suggests

that, while a keystroke timing attack may not be possible, a passive observer may be able to determine message length in addition to user-specific information, such as typing speed and identity, as well as host-specific information, such as device type and operating system family.

Keywords: *keystroke dynamics, web application, instant messaging, IM, side-channel attack*

Background

Web-based IM communications are thought to be protected from eavesdropping via the implementation of HTTPS. However, side-channel leaks and keystroke timing attacks threaten the confidentiality of users and therefore also threaten the security of instant messaging, even when those communications are encrypted. A side-channel provides the ability to observe protected information that an attacker can use to exploit the implementation of a system versus the design of that system. Side-channels come in the form of shared microarchitectural and architectural resources, as well as electromagnetic and acoustic emanations during operation (Demme et al., 2012). Information leaks may occur through normal system usage as soft and physical components interact in unintended ways. Furthermore, unique signatures are created on systems based upon a user's inputs, such as URL requests or encryption key information, that are entered into a program.

Within web applications, system state transitions are normally triggered by user input (Chen et al., 2010). Techniques, such as Asynchronous JavaScript and XML (AJAX), are becoming utilized more frequently within interactive and dynamic web interfaces. Similar techniques are used within the graphical user interface elements of web applications (e.g., search auto-suggestions). As a result, even the smallest interactions, such as selecting a radio button, can generate web traffic. This design potentially allows an attacker to map out the possible input values to network traffic patterns and use this mapping to identify user actions or identity from encrypted traffic.

Keystroke timing attacks exploit a user's keyboard input (Monaco, 2018). Attackers can use side-channels in order to acquire keystroke timings which can occur, e.g., through microarchitectural attacks that enable the recovery of keyboard interrupt timestamps (Schwarz et al., 2017). Prior research suggests that keystroke timing attacks against IM can be performed by employing the use of "a class of inline interception mechanisms," that transmit data covertly when situated at an input device nested inside a trusted environment (Shah et al., 2006). Additionally, since keystroke loggers generally do not exfiltrate data, the use of a covert channel in conjunction with a keystroke logger enables leaking data remotely to a receiver that is monitoring the traffic, even if the traffic is encrypted and the receiver is several hops away.

Recent work on the use of timing analysis for keystroke recognition has resulted in the capability to remotely correlate packet intervals with keystroke recognition (Monaco, 2019). This work showed a text recognition accuracy up to 15.83% assuming the user types common English words. We are expanding on this work by reviewing several commonly used web-based IM applications. Specifically, we are looking at whether IM metadata induced by keystroke events could lend itself to a keystroke timing attack.

Findings and Conclusions

To measure the correlation between keyboard events and network traffic, keyboard events, including their timing as well as the network traffic generated, were collected and compared. A network with three hosts was created. This included two physical clients running Windows 10 (client1 and client2) and a monitor host running Kali Linux. The monitor was connected to a network TAP fabricated based on a widely used design (Schut et al. 2015; Karunaratne, 2009) which allows for isolating capture of Transmit (Tx), Receive (Rx), or both directions of network traffic flow. The TAP is physically incapable of injecting traffic onto a network and passively throttles network bandwidth to 100Mb or less (Gómez, 2003). Substantial effort was taken to acquire an Internet-facing network connection that was unmonitored. The ISP connection was logically located behind a firewall with no further security between the outbound connection and the cloud.

To provide accurate metrics when comparing physical keystrokes with network traffic, keylogging software was installed on both clients. The keylogging software used during these experiments was written specifically to log the timing of keypress and key- release events alongside the logged characters. Wireshark was used on the monitor to capture traffic through the TAP and netsh, a native MS command-line utility which allows configuring and displaying the status of various network communications, was used to capture the clients' network traffic (McIllece et al., 2020). Collecting traffic at the clients, as well as at the TAP, enabled correlation of network traffic events and isolated client-initiated traffic.

Network traffic between each client and any server with an Internet Protocol (IP) address associated with the IP range(s) assigned to the IM server's parent company was isolated. This left for analysis only the network traffic containing either message content or control data in their payload. The decrypted PCAP files were used to search for the network traffic directly associated with the various aspects of message traffic. More specifically, viewing the decrypted traffic allowed the pinpointing of network traffic with payloads directly pertaining to message content. This same general procedure was performed for the network traffic collected during the different sessions focusing on each IM server.

With regards to message traffic, all three platforms followed the same basic operating procedure. The platforms would establish an individual TCP session between the IM server and each client, and these sessions were used for all IM based traffic. The message content data and session control data are transmitted through the same encrypted TCP stream.

The timings of network packets and keyboard events were compared by combining the keyboard event timestamps with the packet timestamps and then sorting this list. The keyboard events were then matched up to network packets by comparing the difference between successive timestamps. Message meta-information (e.g., first keystroke, pausing beyond the server's time-out period, pressing Enter) were found to directly cause network traffic. This negates the possibility of direct keystroke analysis based on timing of network traffic. It does not, however, remove the possibility of other potential threats such as user identification, message length analysis, and device fingerprinting.

Recommendations for Further Research

The use of IM packet timings as a vector for a keystroke timing attack does not appear to be a viable option. This is based heavily on the fact that packets are not produced on a per-keystroke basis in the applications examined. However, because there do exist a variety of packets that are immediately induced by keyboard events, other attacks on user privacy, such as user or device fingerprinting, may be possible.

None of the three IM web applications had direct keystroke-to-network event correlations for all keystrokes, but all three applications did have predictable network traffic associated with the first keystroke and pressing Enter to send the message. Both Facebook and Google implement an interval-based polling to check if a user was actively typing, which results in an activity update notification. Kiwi would only send a status notification change at the start of typing and then after a message was sent or if the user canceled the message.

This study did illuminate a method of consistently separating packets which contained text from those that did not. This finding was based on backward analysis and predictable behavior under a controlled environment that was not designed to simulate the multitude of conditions found in the wild. The detection of IM message packets based on packet size ranges will need to be further validated against a variety of conditions to assess wide-scale applicability. Further, review of the encrypted packets provided a direct correspondence between packet size the number of characters in a message. This can be used to ascertain the length of each message sent, providing a possible method of user fingerprinting. These results are worth future investigation.

There does appear to be some evidence relating specific keystroke events with network traffic that might be used to fingerprint a device. Indicators, such as characteristic peaks in the power spectral density of the timings of keystroke-induced packets, may indicate operating system family or device. Research into the clock frequencies of various operating systems and hardware combined with a larger test corpus may reveal a method of remote device identification.

Finally, the use of an automated text input and response application would produce more consistent keystroke timings throughout the IM traffic captures. For our experiments, the use of human agents for chat dialogue did not impact our results. However, automating this process may further reveal the behavior of IM web applications, such as a fine-grained measurement of the delay between pressing a key and the network packet being transmitted.

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NPS-20-N033-B: Identifying Anomalous Network Flow Activity Using Cloud Honeypots

Researchers: Dr. Neil Rowe and Mr. Thuy Nguyen
Student Participation: Jeffrey Dougherty CIV, LCDR Matthew Bieker USN, and LT Darry Pilkington USN

Project Summary

This work addressed efficient and effective implementation of honeypots (decoy devices) in cloud services. Honeypots are essential tools for detecting new attacks on computers and networks, and cloud services are distributed processing systems that can be used to provide great flexibility in software deployment. The subtype of honeypot we investigated was for industrial control systems (ICS) that manage electrical-power systems. We started with two integrated software frameworks called Conpot and GridPot, and added new obfuscation techniques, new simulated features of a fake electric grid, and new interfaces that looked like real power-plant controls to increase their deceptive power. These deceptions were effective in our first experiments with a standalone honeypot, as we were attacked twice by a sophisticated military adversary as well as by many other less sophisticated attackers. In our second experiments, not yet complete, we deployed the same honeypots at two cloud sites in the U.S. and in Singapore. We saw definite differences between all three deployments, showing that context is very important in deceiving attackers and collecting useful data about their attacks. We were concerned deployment in the cloud could be detected by attackers and discourage their investigation, but we saw no evidence of that; apparently, enough real electric-generation systems are deployed in the cloud today that they are not suspicious. We conclude that honeypots for industrial control systems using cloud services are a useful tool for information security.

Keywords: *honeypots, cloud services, industrial control systems, power plant, electric grid, cyberattacks, deception, Conpot, GridPot, obfuscation, adversaries*

Background

We have deployed honeypots (decoy devices) for over 15 years at the Naval Postgraduate School (Rowe & Rrushi, 2016), and have derived much useful information about cyberattacks from them. The technology for implementing them is increasingly mature, and a variety of deceptions can be used to make them more effective (Rowe, 2018). In the past two years, we have explored honeypots for industrial-control systems, such as those in power plants. The Navy has many such systems in operation on ships, and also uses them onshore on bases similarly to civilian utilities, but they are especially vulnerable to cyberattacks because of the difficulty of updating their software. Honeypots for these systems are also difficult to implement because they must simulate specialized processes like energy delivery, rather than well-known network communications methods as by most honeypots.

Cloud services would seem a good way to implement honeypots since many cyberattack campaigns choose targets and methods randomly, and having many targets permits seeing a more complete spectrum of attacks (Atadika, Burke, & Rowe, 2019). Industries are increasingly using cloud services for supervisory control of manufacturing, power plants, and other industrial control systems. However, they may not be convincing to cyberattackers because cloud usage for these purposes is relatively recent, and detection of the use of cloud services is often easy through identification of the owner of its Internet site, so many cyberattackers should be suspicious of sites in the cloud claiming to be industrial control systems. At least in theory – so many cyberattacks are automated today that rarely do humans attackers inspect the characteristics of a site anymore. The only reliable way to assess the suspiciousness of a cloud honeypot is to do experiments with real cyberattackers. Fortunately, cyberattackers need not be recruited, as putting any site up on the Internet usually attracts attackers within an hour, and at a higher rate for industrial control systems than for traditional computer systems (Hyun, 2018).

Findings and Conclusions

The honeypots we built in this research used two open-source software frameworks, Conpot (Antonioli et al., 2016) and GridPot (Redwood, 2016). Conpot is a low-interaction honeypot, meaning that it has limited simulation capabilities, but it does implement the first few steps in many common communications protocols to catch initial connection and subversion attempts. GridPot is an extension of Conpot to provide more detailed interaction with attackers simulating electrical-power delivery systems, and uses GridLab-D, a power-system simulator from Pacific Northwest Labs. Work in 2019 installed both, but they encountered many problems and got only a few weeks of data, yet they did seem to fool attackers (Rowe et al., 2020). Overall, documentation and installation instructions were poor. Many required packages for GridPot had not been updated since 2016, and we had to find upgrades that would work with Conpot without major changes to GridPot. Once running, the Conpot portion did not impress attackers because of its limited simulation capabilities (Hyun, 2018). GridPot did more detailed simulation, but its implementation lacked parts for which we had to write our own code. We added additional camouflage in the names used in Conpot and GridPot since default names are easy clues for identifying honeypots. Finally, neither framework provided attackers with access to the deeper Supervisory Control and Data Acquisition (SCADA) levels of industrial control systems, so we added a standard Microsoft SCADA interface for the Windows operating system to the simulator.

First, we ran a standalone honeypot implementation without the SCADA interface and collected useful attack data. We then connected the interface, and it was attacked by a military adversary and many (but not all) logs were erased (Dougherty, 2020). We fixed the observed vulnerabilities, started it again, and were attacked again, this time by an adversary trying to manufacture cryptocurrency, at which point we turned it off. Clearly this Microsoft interface console was not well debugged. Next, we obtained a cloud account with Digital Ocean, and installed the same honeypot implementation, minus the SCADA interface, in a virtual machine (Bieker & Pilkington, 2020). We ran it at two sites, one in California and one in Singapore, to test regional differences in attacks; it will continue running until November.

Preliminary results showed significantly more traffic on the cloud sites than on the standalone non-cloud sites, so attackers are not discouraged by the cloud implementation. We also saw significant differences between the U.S. and Singapore traffic, which suggest some security advantages of international cloud services. These results confirm that cloud honeypots are feasible and effective for collecting intelligence on new cyberattacks on industrial control systems.

Recommendations for Further Research

More experiments with cloud honeypots need to be conducted. Since we observed regional differences, hundreds of honeypots should be set up all over the world and their outputs compared. Cloud services make this much easier than setting up sites individually, and we saw no significant disadvantages to them, so they clearly should be the preferred implementation. Having more detailed simulation capabilities for industrial control systems increased cyberattacker interest and the amount of activity on our honeypots, so simulation features should be enhanced. A Linux version of a SCADA interface should be tested to avoid the vulnerabilities of the Microsoft product based on the Windows operating system. As for data analysis, more can be done to find new cyberattacks, as there are a wide variety of methods we did not have time to try. Being able to compare attacks across many different sites should make it easier to see past the randomization of many attacks. After termination of this grant in October, three students will be continuing this work, including Bieker & Pilkington, who graduate December 2020, and Washofsky, who graduates September 2021.

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NPS-20-N033-D: Machine Learning Techniques for Identifying Anomalous Network Traffic

Researchers: Mr. Victor Garza, Mr. Brian Wood, and Dr. John Monaco
Student Participation: LCDR John Ross USN, LT Nathaniel Males USN, MAJ Raymond Blockman USA, and LT Natasha Niemann USN

Project Summary

Cyber investigations often involve analysis of large volumes of log files, including network flow data. Machine learning (ML) techniques allow analysts and examiners to more quickly identify traffic flows relevant to the investigation. The research will focus on the analysis of network flow data generated by the Audit Record Generation and Utilization System (ARGUS). Examples of anomalous traffic patterns of interest (not an exhaustive list) include traffic spikes, malware beaconing, command and control (C2) activity, data exfiltration, and scanning.

The objective of the proposed study is to analyze network flow data with ML and heuristics algorithms to optimize time spent by analysts and investigators during cyber network forensic investigations (including, but not limited to, cyber incident handling and incident response investigations). We are analyzing ARGUS, and other network flow application data, with ML algorithms, with a focus on targeting and optimizing indicators-of-compromise (IOCs). ML is being leveraged to mine network flows to optimize the determination and identification of an ongoing compromise, or historical evidence of compromise (mining C2 channel data, beaconing, data exfiltration, unexpected, encrypted traffic, or other anomalous network traffic).

After an extensive review of various market solutions, we found that there is a general paucity of specific products addressing forensic analysis of anomalous network traffic several vendor products are headed in the direction of using ML algorithms that can be considered as a solution in analyzing network traffic flow. An analysis of the 10+ possibilities have been produced.

Keywords: *machine learning, ML, net flow, anomaly, cyber, Audit Record Generation and Utilization System, ARGUS*

Background

Cyber investigations often involve analysis of large volumes of log files, including network flow data. ML techniques allow analysts and examiners to more quickly identify traffic flows relevant to the investigation. The research will focus on the analysis of network flow data generated by the Audit Record Generation and Utilization System (ARGUS). Examples of anomalous traffic patterns of interest (not an exhaustive list) include traffic spikes, malware beaconing, C2 activity, data exfiltration, and scanning.

Previous work on use of existing ML algorithms or techniques has been examined to the analyze network flow data, searching for, and focused on, indicators of compromise (IOCs), and their rapid identification for investigators. Several vendors (10+) who focus on ML techniques in this area were contacted and their solutions studied. Examples of several COTS network flow applications have been effective in providing promising results. We have reviewed current solutions and evaluated their utility for the Navy.

Subject matter experts have access to background material and can provide feedback on the appropriateness of proposed approaches, methodologies, principles, and tactics for integrating ML and network flow data into operational investigations. Thesis students are analyzing proposed opportunities for ML and data flow applications to determine their value added.

Findings and Conclusions

Research Questions

1. Which, if any, existing ML algorithms or techniques could be usefully applied to the analysis of network flow data?
2. What operations and maintenance considerations apply to long term utilization of ML algorithms against evolving cyber threats?
3. What caveats/limitations must be considered by consumers of alerts produced by ML analysis of network flow data?

Methodology

Previous work using ML algorithms/techniques were identified and analyzed to determine which ones could be usefully applied to the analysis of network flow data, searching for, and focused on, IOCs, and their rapid identification for investigators. The authors attended a major security conference (RSA 2020) in February 2020 to meet with vendors to discuss their solutions. A Gartner review of several solutions was helpful in our analysis (Orans et.al, n.d.) Each solution was then described and analyzed.

For the thesis research analysis is being conducted on ARGUS type data and on proposed opportunities for ML and data flow applications to determine their value added.

Findings

Products performing forensic analysis of anomalous network traffic are not a common theme among the cybersecurity vendors. Most solutions focus on detecting and reacting to intrusions.

More automated and manual features are being used in Network Detection and Response (NDR) solutions. ML applied to network traffic is helping to detect suspicious traffic missed by other tools.

Recommendations for Further Research

The following recommendations are given to improve infrastructure security. Behavioral-based Network Detection and Response (NDR) tools should complement signature-based detection solutions. NDR should be included as a feature solution as part of the security information and event management (SIEM) and firewall. NDR vendors with a clearly defined response strategy should be considered.

Users should use the following methods to identify the most relevant vendors. They should consider vendors who analyze raw network packet traffic/traffic flows in real/near-real time and traffic that crosses the network perimeter; traffic that moves throughout the network without crossing the perimeter must be monitored and analyzed. Normal network traffic should be modeled, and suspicious traffic should be highlighted. In the detection of network anomalies, non-signature-based detection behavioral techniques, e.g., machine learning should be used. Automatic and/or manual responses also should be used to respond to the detection of suspicious network traffic.

Solutions that contain the following requirements should be avoided: prerequisite components (e.g., SIEM or firewall platform); emphasis on network forensics vs. detection functionality, through the storage and analysis of full network traffic data; using log analysis as a primary means of investigation; focusing on analytics of user session activity technology; and traffic analysis focusing on Internet of Things or operational technology environments.

Vendors will continue to focus on detection and response capabilities. Their ability to detect suspicious patterns in encrypted traffic will be emphasized with some adding native capabilities in their sensors (the termination, decryption, and analysis of Transport Layer Security (TLS) traffic). Most vendors will improve their ability to detect suspicious traffic by removing the requirement to decrypt TLS traffic and inspect the payload (e.g., the detection of suspicious secure sockets layer (SSL)/TLS Server Certificates). Techniques such as analyzing individual packet length, timing between packets, the connection duration will also be used to detect suspicious traffic.

Automated response improvements will be accomplished via expanded partnerships with firewall vendors, network access control vendors, security operations automation response vendors, endpoint detection and response vendors. Manual response solutions will involve improving threat hunting and incident response functions by improving workflow features.

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NPS-20-N052-A: Naval Aviation Readiness Performance Pricing Model Integration (Phase 2) (Continuation)

Researchers: Dr. Douglas MacKinnon and Dr. Jefferson Huang
Student Participation: ENS Matthew Luerman USN

Project Summary

The Naval Aviation Enterprise utilizes Performance/Pricing Models (P/PM) in its budgeting process, enabling a data-driven, computational approach toward achieving performance outcomes. One of these key outcomes is Carrier Air Wing (CVW) Operational Availability (Ao), which dictates a desired level of readiness among the Navy's CVWs. There is a lack of integration between the major P/PMs used in the budgeting process, which limits the decision maker's understanding of how the P/PMs responsible for depot-level maintenance connect to Ao. To address this gap, we perform a data-driven assessment of how the P/PMs used in the aviation budgeting process connect to Ao. Due to limited historical data, our analysis focuses on identifying linear relationships between the P/PMs and Ao. This research effort culminated in a mapping of P/PM inputs and outputs to all four elements of Ao. Key inputs and outputs that could potentially be altered to improve Ao cost efficiently were also identified. The use of limited historical data prevented the categorization of statistically significant relationships to Ao as causal.

However, follow-on research that looks more closely at individual models may develop an understanding of causal mechanisms that can further inform the use of conceptual mappings now developed in this study.

Keywords: *Operational Availability, readiness, Ao, performance/pricing model, P/PM, Flight Hour Program, cost per hour, CPH, Flight Hour Program, FHP, Flight Hour Resource Model, FHRM, Flight Hour Projection System, FHPS, Airframe Depot Readiness Assessment Model, ADRAM, Engine Depot Readiness Assessment Model, EDRAM, carrier air wing, CVW*

Background

The Naval Aviation Enterprise utilizes P/PMs in its budgeting process, enabling a data-driven, computational approach toward achieving performance outcomes. The aviation budgeting process is driven by five major models, four of which were examined in this study (the legacy Sparing model was excluded in the prior research phase since it is being replaced with a new model). The Flight Hour Program (FHP) consists of the Flight Hour Resource Model (FHRM) and Flight Hour Projection System (FHPS). FHRM builds the flight hour requirement for Naval Aviation. The FHPS then builds an estimate for the cost per hour (CPH) of those flight hours for every aircraft type/model/series (TMS), which in turn helps inform the number of flight hours that are budgeted in a given execution year.

The Depot Readiness Assessment Model (DRAM) suite is composed of the Airframe Depot Readiness Assessment Model (ADRAM) and the Engine Readiness Assessment Model (EDRAM). The DRAMs plan depot-level maintenance for airframes and engines at Fleet Readiness Centers (FRCs), which carry out the most complex and costly maintenance events. Flight hour requirements from FHP help build the EDRAM requirement, but ADRAM is only connected to the other models by the Aircraft Inventory Exhibit (A-II), Flight Line Entitlement (FLE), and Aircraft Program Data File (APDF). Additionally, there is no feedback from the DRAM suite back into the FHP.

Our planned Ao metric is derived from the Fleet Response Training Plan (FRTP), and is broken down into four elements: Deployed, Surge/Sustainment, 90-Day Surge, and 180-Day Surge. CVWs in a Deployed level of readiness are currently on deployment. CVWs at a Surge/Sustainment level of readiness can immediately deploy if necessary. These CVWs are either about to deploy, have just finished a deployment, or are forward deployed. Air wings at a 90-Day Surge readiness level can deploy within 90 days of their need being identified. Likewise, a 180-Day Surge readiness indicates the ability to deploy within 180 days. All CVWs are at least at a 180-day surge readiness level.

Findings and Conclusions

This research effort succeeded in identifying links from each P/PM to Ao and demonstrated the benefits of analyzing Ao utilizing the entire modeling architecture. We were able to establish connections from FHP to Deployed readiness, and from ADRAM and EDRAM to Deployed, Surge/Sustain, and 90-Day readiness levels.

Analysis of FHP connected Schedule A aircraft inventories, CPH elements, and budgeted flight hours (BFHs) to Ao. Although a linear decrease of Deployed CVWs over the past decade could increase the possibility of identifying superfluous connections, we found that BFHs and CPH maintained their connections to Ao even after standardizing by the number of aircraft. AVDLR and Maintenance costs appear to be the primary drivers of the connection between CPH and Ao, and their reduction should be prioritized moving forward.

Despite identifying a robust set of connections between FHP and Deployed readiness, we were unable to identify any links to the other three Ao elements. A broader analysis of the P/PM architecture was needed to develop a more comprehensive understanding of all Ao elements. Fortunately, when we expanded our analysis to include ADRAM inputs, we were able to identify ties between ADRAM and Surge/Sustain and 90-Day Ao.

Analysis of ADRAM identified backlogged maintenance, distribution of funding between depots, and Strike/Electronic Warfare (EW) and Rotary budgets as the key drivers of the links between ADRAM and Ao. We found that both the cost of backlogged maintenance events and the number of backlogged maintenance events correspond with an increase in 90-Day readiness. This finding may mean that prioritizing the least expensive maintenance events could improve readiness in a cost-efficient manner. We also found that the ratio of funding allocated to the two depot-level FRCs in Naval Air Station (NAS) Jacksonville and NAS North Island correlates to Deployed readiness in the historical data. Future research could potentially conduct a comparative study of these two FRCs and investigate whether differences in their operations drives this connection to Ao. Lastly, the links between Rotary and Strike/EW budgets to Ao were not consistent with our initial intuition. The finding that increased ADRAM funding corresponds to a decrease in readiness should be investigated in future work. It may be that ADRAM funding is itself indirectly driven by Ao, and that depot-level maintenance is planned around deployment schedules.

Analysis of EDRAM links to Ao succeeded in identifying additional connections to Deployed, Surge/Sustain, and 90-Day Ao. After looking at each P/PM separately, we failed to identify links to 180-Day readiness. However, including ADRAM and EDRAM in our analysis framework has provided a better understanding of the other three Ao elements.

The two main drivers of connections between EDRAM and Ao are the engine readiness goals (ERGs) and total engine inventories (TEIs) for CVW aircraft. It appears that increasing ERGs tends to correspond to a decrease in readiness, which did not match our initial expectations. Like ADRAM, this inverse relationship may be a result of planned Ao driving EDRAM funding. Follow-up research should be conducted to develop a better understanding of the causal mechanisms driving this inverse relationship. The finding that an increase in TEIs per aircraft corresponds to a decrease in Deployed readiness is another counterintuitive result. This relationship might also receive closer investigation in future research, as it may be a sign that engines are being overfunded.

An exploratory analysis of interactions between P/PMs yielded some positive initial results. When we looked at connections between ADRAM and FHP at a high level, we were able to establish links to all four Ao elements. Based on the correlations to Ao in the historical data, it may be worthwhile to attempt reducing ADRAM funding relative to BFHs and BFH costs for Strike/EW and Rotary aircraft. Developing a better understanding of the causal mechanisms linking ADRAM to Ao may inform our understanding of the effects of interdependencies between ADRAM and FHP.

Our analysis of interactions between EDRAM and FHP failed to provide links across all Ao elements, yet we did identify some additional connections to Deployed and Surge/Sustain readiness. We observed results that are consistent with the interactions between ADRAM and FHP, where increases in EDRAM funding relative to FHP costs correspond to a decrease in readiness. If the identified correlations represent some underlying causal effect, it may be worthwhile to reduce EDRAM funding relative to BFH costs. Again, the negative correlation to readiness may indicate an inefficient allocation of funding to EDRAM, or it may simply be an artifact of maintenance scheduling.

A similar exploratory investigation of links between ADRAM and EDRAM interactions to Ao failed to yield any significant links. Budgets for each TMS group were compared, along with backlogged maintenance. Further study incorporating the other model inputs may succeed in identifying useful connections.

Recommendations for Further Research

The reliance on historical data made this an observational study, preventing any conclusions from being drawn about cause-and-effect relationships. To work toward building an integrated model to optimize Operational Availability, a data farming approach could be utilized to generate data from many model runs with a wide range of model inputs. Analysis of a larger designed dataset would allow for a clearer understanding of model interactions that were too complex or too small in magnitude to identify with the limited number of data points available in this study.

While Operational Availability is an important readiness metric, the complications associated with its demand-driven nature combined with limited historical data might mean it would be better to conduct future research efforts using an alternative readiness metric. However, if at some point it is possible to examine the internal modeling processes, it might be beneficial to conduct another research effort focused on Ao.

The DRAMs utilize assumptions and decision rules which may result in sub-optimal funding decisions. When funding falls short, these models defer maintenance for the TMS with the smallest excess availability, when it would seem to make more sense to defer TMS with the largest excess availability. With the selected TMS, these models also defer the most expensive maintenance tasks. This methodology is neither guaranteed to be optimal nor representative of actual operating practices. Work should be conducted to see if optimization methods can be utilized to minimize the decrease in readiness for a given level of funding.

NPS-20-N053-A: Maritime Readiness Performance/Pricing Model Integration (Phase 1)

Researchers: Dr. Paul Beery, Dr. Eugene Paulo, Dr. Douglas MacKinnon, and Dr. Bryan O'Halloran
Student Participation: Tenley Chlaupek CIV, Daniel Monroe CIV, Ishan Patel CIV, and Johanna White CIV

Project Summary

The United States Navy utilizes performance/pricing models (P/PMs) to assess fleet readiness from both operational and maintenance perspectives. Currently, those models are largely independent and there is no assessment or evaluation of the impact that changes in one model may have on the analytic results in another model. To highlight the connections and interfaces between those models, this project develops a total readiness integration model (TRIM) that utilizes a model-based systems engineering (MBSE) approach to integrate existing Department of the Navy models of ship maintenance and ship operations. The project decomposes the existing models into traceable tiers, develops visual representations of underlying mathematical representations, and highlights data flows and interfaces that enable operation of the existing model. The project conducts an executable assessment of the logical structure of the TRIM, utilizing a commercial MBSE tool called Innoslate, to identify potential bottlenecks and challenges associated with data collection and definitions across the existing maintenance and operations models. That assessment utilizes a Monte Carlo simulation to identify the activities that create bottlenecks between ship operations and maintenance as well as areas for potential improvement to overall availability. Results suggest that, for the ship classes studied, there exists up to 2.5 months of potential opportunity to increase ship availability within the existing maintenance and operational profiles.

Keywords: *readiness, operational availability, performance/pricing models, model-based systems engineering, MBSE, Ship Operations Model, Ship Maintenance Model*

Background

To support maintenance and operations of fleet readiness, the United States Navy adheres to a rotational schedule of operations, maintenance, and funding. The Navy utilizes a Fleet Response Plan (FRP) to formalize that rotation and support associated planning and analysis (Pickup, 2012). Beyond the FRP, the Navy utilizes P/PMs to define the mathematical relationships that calculate fleet readiness. Specific P/PMs, the Ship Maintenance Model (SMM) and Ship Operations Model (SOM) are of particular interest to the Navy due to their ability to support informed development of future fleet requirements through trade-off analysis. There is a motivation to integrate the analysis of fleet readiness with the Planning, Programming, Budget, and Execution (PPBE) process, specifically the Program Objective Memorandum (POM) developed as part of the PPBE process. This integration is complicated by the lack of a shared terminology between Office of the Chief of Naval Operations (OPNAV) organizations. A primary motivation of this project is to conduct decomposition of the SMM and SOM, which are the responsibility of the OPNAV Assessment Division (N81) to communicate findings related to fleet capabilities to the OPNAV Programming Division (N80), the main architect of the POM.

The SMM collects inputs to produce a monetary requirement and schedule for ship maintenance. The SMM is based on the maintenance schedule of fleet vessels, the expected costs associated with private industry, the anticipated force structure of the fleet, and projected capability of naval shipyards and Regional Maintenance Centers. The SMM organizes input data into broad categories such as individual ship availability, hiring plans, phasing, reimbursable material cost, workloads, and maintenance schedules. This data is transformed through assessment of workloads and pricing projections into projected contractor requirements, labor costs, and workforce requirements.

The SOM is focused on operational requirements and produces an assessment of fleet operational availability (Ao). That assessment is driven by multiple inputs, such as force management schedules, anticipated operational days, fuel usage rates and prices, and hull usage. Those inputs are systematically varied to produce an estimate of the anticipated Ao over multiple timeframes.

Integration of stove-piped models is a focus area within MBSE. Specifically, MBSE approaches may improve the clarity, traceability, interface definition, and modularity of models such as the SMM and SOM. In practice, this is facilitated through use of an MBSE compliant architectural tool such as Innoslate, Vitech CORE, or Cameo Magic Draw, which enable traceability through a consistent underlying ontology and decomposition of previously developed models.

Findings and Conclusions

The TRIM, developed consistent with current MBSE standards, is used to integrate the activities described in the SMM and SOM and to calculate Ao as defined by the SOM. The development of an MBSE compliant architecture serves two purposes. First, it highlights the relationships between the SMM and SOM by developing them in a single environment where any inconsistencies in data definitions result in model error. It also facilitates reuse by representing the activities considered in both the SMM and SOM as actions, accepting the key data fields from each model as inputs, and calculating the items produced by the SMM and SOM as outputs.

The TRIM is comprised of both a functional and a physical architecture component; the functional architecture decomposed the activities, sub-activities, and calculations performed in both the SMM and SOM, and the physical architecture defined the data element commonalities and interfaces between the SMM and SOM. This facilitates development of an integrated, executable architecture model that highlights the impact that the ordering of activities and calculations can have on the end-to-end analysis of the SMM and SOM based on the dependence between those models on creation of individual data elements.

The TRIM predicted Ao based on total ship deployment, the total number of ships currently in a sustainment phase, and the total number of ships in integrated and basic phases. The TRIM was designed to predict Ao over a 27-month timeframe where decisions regarding distribution of the fleet were made contingent upon cost and schedule expectations for each ship in each phase. Each ship is also assumed to transition, at a variable rate, between an underway state and a non-underway state. A Monte Carlo analysis was conducted for 2,000 runs of the TRIM where the duration of each activity is varied. Results indicate that, across the fleet for an average 12-month timeframe, a generic ship is able to complete all operational activities defined by the SOM and SMM in approximately 9.5 months (with a standard deviation of approximately 4 months). This suggests that there may be an opportunity to increase overall availability through proper scheduling and planning of the approximately 2.5-month delta between the 9.5-month total activity time and the expected 12-month total activity time.

Recommendations for Further Research

Further development of the total readiness integration model (TRIM) is required to increase the confidence in the model recommendations. The TRIM suggests that each ship is only obligated to either operational or maintenance activities for 9.5 months in a 12-month timeframe. Several follow-on courses of action are possible based on these results. First, it is possible that there is an opportunity to increase the underway time for each ship by up to 2.5 months, which would, by definition, improve the operational availability (Ao) of the fleet. This course of action is dependent on further refinement of the model to decrease the standard deviation (currently estimated as approximately 4 months) associated with the mean activity estimate of 9.5 months. As currently constructed, each of the activities represented in the model has a broad range of potential durations; accordingly, there is substantial variability in the model output. This may be improved through refinement of the time duration associated with each activity or through a revision of the activities associated with each ship in both the Ship Maintenance Model (SMM) and Ship Operations Model (SOM).

Beyond tweaking of the durations and costs associated with individual actions and activities contained in the current version of the TRIM, it is also possible to expand the existing model to incorporate several elements that, due to time and classification constraints, were not considered as part of the analysis. Specifically, nuclear powered ships and submarines were not included as part of the analysis. Further, multiple decisions that may impact the long-term (beyond 27 months) behavior of the model, such as base maintenance and fleet modernization were beyond the scope of this model.

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NPS-20-N109-B: Development Time of Zero-Day Cyber Exploits in Support of Offensive Cyber Operations

Researchers: Dr. Gurminder Singh, CDR Alan Shaffer USN Ret. and Mr. Charles Prince
Student Participation: CPT Konstantinos Bompos FORNATL GR

Project Summary

Zero-day vulnerabilities are vulnerabilities that have not previously been identified and thus are in their zeroth day of existence. They are the most potentially damaging from a cyber defense perspective because the defender is unaware of their existence, and a malicious attacker can exploit them to take control of a system without the owners' knowledge. Zero-day vulnerabilities are also valuable for offensive cyber operations (OCO) as they may be highly exploitable.

This research reviews zero-day vulnerabilities in different resources and examines their overall impact on targeted system security. We discuss characteristics of a system that increase its susceptibility to zero-day vulnerabilities, and present security measurements to improve the zero-day vulnerability awareness of the defender. We present techniques for reducing the development time of zero-day exploits.

We found that a zero-day vulnerability in a system can compromise the entire security infrastructure of the organization. Systems with layered defenses are able to better restrict and mitigate the effects of zero-day vulnerability exploitation because a layered defense will force attackers to penetrate each layer, reducing the effects from a single vulnerability. Additionally, we found that systems with a higher level of complexity are more likely to contain zero-day vulnerabilities, since this complexity will tend to mask their existence.

While publicly available data on zero-day exploitation is limited, we found that training research teams in Capture-the-Flag (CTF) exercises and similar cyber war games can heighten their skills in identifying patterns in the discovery of zero-day vulnerabilities. In addition, stockpiling unexploitable zero-day vulnerabilities by hiding their existence can allow OCO forces time to develop exploits.

We recommend continued work in development of an automated tool for zero-day vulnerability discovery. This tool will help in identification of zero-day vulnerabilities in software products, as well as aiding in discovery of exploitable zero-day vulnerabilities on a target system.

Keywords: *computer system security, zero-day vulnerability, cyber-attack, exploit, offensive cyber operation, OCO*

Background

A vulnerability in computer software is a loophole in the computer code and/or its configuration that can possibly compromise the security of a computer system (Shahzad, Shafiq, & Liu, 2012). An adversary can exploit such vulnerabilities and take control of a system without the approval or, in many cases, without the knowledge of its user. Among an adversary's actions, zero-day exploits make use of a vulnerability whose existence is still unknown to computer system defenders and software vendors. These vulnerabilities are potentially the most damaging from a cyber defense perspective because the defender has no knowledge of their existence, and a patch for the affected software has not yet been developed (Bilge & Dumitraş, 2012)

The security level of a computer system is often measured by the total count of vulnerabilities on the system and the time required to exploit them, or the time required for the implementation and distribution of software patches to mitigate the vulnerabilities. In the face of zero-day vulnerabilities, these measures can become skewed because a full understanding of existing vulnerabilities is not possible. For the adversary, developing a reliable zero-day exploit can be challenging, but it can be extremely rewarding since it will be unknown to defenders, and ideally, will work on any configuration of a vulnerable target (Ablon & Bogart, 2017).

Zero-days attacks are more frequent today than they were in the past, and they remain undercover for long periods of time, making them much more pernicious than other types of attacks. The time to develop a zero-day exploit must include the time to identify a zero-day vulnerability, and then the time to conduct reconnaissance against target systems. This development time will also depend greatly on the skill and risk tolerance of the attacker, as well as the security configuration of defended systems. Research in 2009 showed that 80 percent of critical vulnerabilities had a functional exploit within ten days of their public disclosure (Kandek, 2009). Moreover, Rand Corporation in 2017 reported that, once the vulnerability researchers detect an exploitable vulnerability, the time for developing a reliable exploit is relatively short, with a median time of 22 days (Ablon & Bogart, 2017).

For these reasons, this comprehensive study of zero-day vulnerabilities is focused on showing them to be a vital factor in cyber operations. The objective of this work is to examine the development time of zero-day exploits and how it can affect cybersecurity in current enterprise systems. The research also examines techniques for reducing the development time of these exploits in order to support OCO.

We achieved the objectives of this study by focusing on the following research questions:

- Primary Question: How does the existence of zero-day vulnerabilities in computer systems, and the time for adversaries to develop exploits against these vulnerabilities, impact the overall level of cybersecurity of that system?

- Secondary Question: How might the total time to develop zero-day exploits, including the time to identify associated zero-day vulnerabilities, be reduced to better support OCO?

Findings and Conclusions

The main goals of this study were to thoroughly examine the impact of zero-day vulnerabilities to cybersecurity and defense, and to analyze how the development time of zero-day exploits can impact OCO. We conducted background research to more thoroughly understand the crucial role of zero-day vulnerabilities in cyber operations, both offensive and defensive, and we analyzed the lifecycle of zero-day vulnerabilities to understand how it affects system cyber defense.

The research focused on how the existence of zero-day vulnerabilities might impact overall system cybersecurity, as determined by not only the kind of zero-day vulnerability, but also by the structure and configuration of the targeted system. Systems with layered defenses may be able to better restrict and mitigate the effects of a zero-day attack because multiple layers of defense force attackers to penetrate each layer. Our research found that systems with higher complexity are more likely to have exploitable zero-day vulnerabilities. Moreover, systems that do not implement segmentation of the network to separate less secure systems, such as user hosts and Internet of Things (IoT) devices, from the critical infrastructure offer a larger surface for zero-day exploitation. Finally, systems with a high zero-day patch rate tend to reduce the time of the exposure window and, therefore, minimize the overall impact of such vulnerabilities to their cybersecurity.

In addition, we examined how the time to develop zero-day exploits, including the time to identify associated zero-day vulnerabilities, may be reduced to better support OCO. In studying statistics of the lifecycle of exploit development, we found that an exploit can be developed, on average, more rapidly than the time taken to discover and patch a zero-day vulnerability (Ablon & Bogart, 2017). A complete answer to this phenomenon is limited by the lack of research on real-world data on zero-day vulnerabilities. However, from our research we can conjecture several factors that could potentially reduce the development time of a zero-day exploit and benefit OCO:

- Training zero-day vulnerability research teams in Capture-the-Flag (CTF) and similar cyber war games can help sharpen their skills, expand their CO toolbox, and identify patterns in the discovery of same class zero-day vulnerabilities. A quite promising approach would be to analyze data on how participants in CTF and war games are working to discover vulnerabilities and use them for training an artificial intelligence (AI) system.
- By stockpiling zero-day vulnerabilities that could not be exploited at the time they were discovered, they can be kept hidden for future use since they might be useful in a future scenario or may become exploitable under different circumstances.
- The increasing use of IoT devices, with their often lack of built-in security or proper security configurations, makes them a valuable target for adversary exploitation. In particular, focusing OCO efforts on discovering zero-day vulnerabilities in these devices offers a potentially rich source of exploitation.

Recommendations for Further Research

The following list presents areas for future research to expand on the work done in this study.

1. Automated zero-day vulnerability analysis tool.

This research was a first step towards deepening an understanding of zero-day vulnerabilities and their exploitability. A goal of the research was to provide a foundational work toward creating an automated zero-day vulnerability analysis tool. This automated tool would scan for zero-day behaviors in systems to identify potentially unknown vulnerabilities. The use of this tool could be beneficial either for the vendors to help them identify zero-day vulnerabilities in their products and patch them, or to offensive cyber operations operators to help them discover exploitable zero-day vulnerabilities on a targeted system.

2. Examine open-source products and compare them to closed-source.

Many organizations today widely use open-source products for their business practices and procedures. Future research could focus specifically on examining whether open-source products are more beneficial for system defenders or their attackers. It should question if the openness of a system helps the vendors discover a zero-day vulnerability quicker, and publicly disclose it and patch it before an adversary can exploit it. Also, it could examine whether the open-source nature of such systems enhances their security by allowing more people to contribute to their defense.

3. AI and zero-day vulnerabilities.

As it was mentioned before, the usage of artificial intelligence (AI) would be a powerful asset in the research and discovery of zero-day vulnerabilities. Data from Capture the Flag and war games could be collected and used for the training of AI. Later, the AI could be tested in a system for discovering zero-day vulnerabilities by comparing their results to those of a human vulnerability analysis team.

4. Study real-world data of zero-day exploits.

Further analysis needs to be done on real-world data of zero-day vulnerability exploits to establish better awareness about them. Knowledge of zero-day vulnerabilities is a great asset for attackers as they can profit by selling this knowledge in the cyber black market. This can dissuade researchers from publishing their results, which makes open academic research difficult. The output from an analysis of real-world data of zero-day vulnerability exploits would be beneficial for the defender's perspective. Defenders and vendors could reduce the impact of a zero-day vulnerability and improve their methodology to discover and patch it. This requires detailed knowledge of how attackers work to reinforce their defenses.

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NPS-20-N152-A: Optimizing Distributed, Collaborative MCM Missions with Unmanned Maritime Vehicles

Researchers: Dr. Sean Kragelund, Dr. Isaac Kaminer, and Dr. Claire Walton
Student Participation: LT Theodoros Tsatsanifos FORNATL GR

Project Summary
Mine countermeasures (MCM) forces must be able to detect, localize, identify, and neutralize underwater threats in complex environments. This requires a variety of sensors not only to detect underwater objects (e,g., sonar "contacts") but also to distinguish actual mines from harmless clutter. Advances in computational optimal control present new opportunities for real-time collaboration between different vehicles for search and identification missions, potentially reducing the MCM timeline. This study leverages prior optimal search and in-stride trajectory generation algorithms for on-demand contact investigation in the presence of false targets. Key findings include new event-driven methods for updating target distributions, new cost functions for optimizing vehicle search trajectories, and new target identification trajectories for visiting a sequence of contacts in minimum time, subject to constraints on vehicle and sensor performance.

Keywords: *optimal search, mine countermeasures, MCM, mine hunting, sonar, mission planning, motion planning, optimal control, autonomous vehicles, unmanned vehicles, unmanned surface vessel, USV, unmanned underwater vehicle, UUV*

Background
Mine countermeasures forces must be able to detect, localize, identify, and neutralize underwater threats in complex environments. These tasks require different sensors. Typically, wide swath sonar is used to detect underwater objects, and high-resolution sonar is used to identify whether these sonar contacts are actual mines or harmless clutter. Search theory defines these two tasks as target detection and contact investigation. Analytical solutions can be derived for optimal search problems with false targets if these targets can be positively identified through immediate contact investigation (Kalbaugh, 1992; Stone, 1989). As a practical matter, however, detection and identification tasks require different sensors that are typically carried by different unmanned vehicles. MCM missions are therefore planned and conducted sequentially, with post-mission analysis (PMA) between vehicle sorties, significantly increasing the duration of the operation. Although automated scheduling methods can optimize the allocation of finite autonomous vehicle resources to complete a sequence of MCM tasks (Bays et al., 2015), the sequential search paradigm itself remains a limiting factor.

Recent advances in computational optimal control have enabled real-time collaboration between dissimilar autonomous vehicles (Cichella et al., 2018, 2020; Kaminer et al., 2017). Generalized optimal control (GenOC) leverages these advances for search applications. Kragelund et al., (2020a, 2020b) apply GenOC to MCM problems by computing optimal search trajectories for realistic mine hunting vehicles and sensors. While GenOC can generate feasible search trajectories in near real-time, the existing problem formulation does not address false targets. Instead, both wide-area search and contact investigation are treated as two separate search problems whose solutions minimize the probability that vehicle/sensor pairs fail to detect an object under specified time constraints. Under this model, the prior distribution of target locations determines the type of search that vehicles perform (Kragelund, 2020a).

Unmanned vehicle teams that can detect and identify mine threats in tandem promise to increase the speed and efficiency of MCM operations. Suppose, for example, that survey vehicles which detect mine-like objects could immediately ask nearby vehicles to investigate these contacts with complementary sensors. This would preclude the need to complete their entire survey missions, conduct PMA, and plan/execute subsequent identification missions. Mission planning methods based on sequential search cannot fully realize this capability, however. A goal of this research, therefore, is to optimize a collaborative search by a team of distributed MCM vehicles. Specifically, the GenOC framework has been extended to a) address problems with multiple, possibly false, targets; and b) generate vehicle trajectories to investigate a list of contacts provided by other vehicles.

Findings and Conclusions

During this study, researchers engaged with subject matter experts from the Mine Warfare Division at the Naval Surface and Mine Warfighting Development Center (SMWDC), the topic sponsor organization. These discussions improved our assumptions and aligned the research with SMWDC's requirement to optimize the effectiveness of next-generation vehicles and sensors for the MCM commander.
This study also leveraged a large body of literature on optimal search in the presence of false targets, including recent NPS thesis research. For example, Bays et al. (2016) combine ideas from decision theory with multi-agent motion control to compute cooperative sensor motions that improve Bayesian classification decisions about threats vs. non-threats. Decker et al. (2007) analyze the probabilities of wide-area search for multiple targets distributed amongst a field of false targets or decoys, a problem analogous to search, detection, and identification of mines for MCM. Finally, McCray (2017) describes a method for planning optimal, semi-adaptive searches which use interim search results to update the probability densities for both real and false targets. Our study analyzed these different probabilistic models, search performance criteria, and Bayesian update methods to incorporate multiple targets into the GenOC motion planning framework.

To cooperate effectively, a UMV team must be able to share information about mission progress, search results, and remaining goals. This study develops ways to update search vehicles' target belief distribution in response to detection events. We define a belief map comprised of the pointwise probabilities for an unknown number of targets in the search region, avoiding the need to estimate the number of real and false targets required by some planning methods, e.g., Bays et al., (2015). Instead, we assume that real and false targets have Poisson-distributed spatial densities and that classifications occur at probabilistic rates (Decker et al., 2007; McCray 2017). Under the original problem formulation without false targets, detection events were always conclusive and effectively ended the search. The new framework, however, updates the belief map by counting true and false detection events, which adds flexibility when defining new cost functions for optimal motion planning. For example, a vehicle team may choose to maximize the overall change in belief map values (i.e., the accumulation of new information) to distribute search effort in areas where it is most effective. Interestingly, the classical optimal search formulation for minimizing risk of target detection failure can also be recovered from this new framework. A key finding from this study is a new, event-driven method for updating target belief maps and planning optimal search trajectories in response to new information.

Contact investigation of detection events requires UMVs to generate trajectories in near real-time, subject to dynamic motion and sensor orientation constraints. This study has produced a method for planning trajectories to visit a specified sequence of targets in minimum time. The approach is similar to the well-known Traveling Salesman Problem, however our method generates feasible trajectories that obey vehicle constraints and designated avoidance zones. This finding enables in-stride UMV tasking to investigate contacts provided by prior intelligence or wide-area search.

Recommendations for Further Research

Many mine countermeasures (MCM) missions are search problems, and recent advances in computational optimal control make it possible to optimize search functions performed by unmanned maritime vehicles (UMVs). Examples include wide-area search to determine optimal MCM geometries and collaborative search to detect, localize, identify, and (when necessary) neutralize mines. Optimal search trajectories can improve upon conventional MCM methods that rely on sequential area coverage missions to clear a designated transit lane, for example. Simulation results have shown that computational optimal control can enable a team of vehicles with complementary sensing capabilities to collaboratively search for mines despite the presence of false targets. Moreover, vehicle search trajectories can be generated in near-real time for on-demand tasking and in-stride replanning. Collaborative search results are preliminary, however, and rely on simplifying assumptions about a vehicle team's ability to share and update information amongst its members. Additional research is needed to validate these assumptions. While our research suggests that optimal search trajectories have potential to reduce MCM timelines significantly, field experimentation with actual UMV platforms is needed to assess their true operational utility.

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N9 - Warfare Systems

NPS-19-N168-A: Analysis of a Lightly Manned Autonomous Combat Capability (LMAAC) Concept

Researchers: Dr. Shelley Gallup, Dr. Johnathan Mun, Mr. John Dillard, and Mr. Ben DiDonato
Student Participation: No students participated in this research project.

Project Summary
As the technology of the "third offset" (artificial and autonomous capabilities) matures, the United States Navy (USN) is embracing some aspects of the capability, including experimentation with the test vessel Sea Hunter. However, ambiguity of its missions has stemmed from tightly intertwined concept of operations (CONOPS)for fleet operations, which have been absorbed and trained for every deploying ship. In addition, trust in an autonomous ship, negative reactions to arming an unmanned vessel, security, and command and control (C2) are all part of the culture of incremental acceptance and change. Combined with the geopolitical situation, particularly in the Pacific, what emerges is an evolutionary "bridge" in which small, fast, lightly manned combatants are called for to provide autonomy with onboard human oversight, and tactical employment of weapons systems. This report details the needs of such a vessel (which we call *Sea Fighter* in this report), combined with unmanned autonomous vessels (e.g., *Sea Hunter)* as sensors, within a sensor grid and truly distributed capabilities. CONOPS are discussed, which are the result of the form and function of this class of warship, while costs and means of acquiring this capability quickly are also examined.

Keywords: autonomy, artificial intelligence, force structure, human and machine teaming, great power competition and strategy in the Pacific Rim

Background
Defense Advanced Research Projects Agency (DARPA) largely built the Autonomous Continuous Trail Unmanned Vessel (ACTUV)—later to become MDUSV, then MUSV, and now synonymous with Sea Hunter—as an experiment in autonomy. Since that time, many years have been spent determining what its mission set should be. At least two conferences were held, one at Navy Warfare Development Command, and another at Naval Postgraduate School. The discussions were at the "what if" level of thinking, mostly void of tactical needs. There are many problems with "potential" and "possible" as determinants of capability—mainly in that they don't exist. and there is a bridge to cross between fully manned (present) and fully unmanned (future), especially when autonomy is also armed. While we test

run at these hurdles, a middle ground sea-control means is needed for the United States' response to the near peer nations and possible domination of the sea lines of communication in the Pacific.

Lightly Manned Autonomous Combat Capability (LMACC) turns "what if " thinking on its head. It is designed to meet a CONOP and strategic mission *now*, rather than built and then refined in a concept of operations. The LMACC has one primary mission: deliver missiles to targets ashore and afloat within the first island chain, while the "leviathan navy" waits out the first round of missile exchanges, to become the second or third round of mission-capable delivery, in a joint operation with long range aircraft and carrier-based fighters. The cruisers, guided-missile destroyers, and aircraft carriers with will not survive the first round of long-range surface to surface missiles inside the second island chain.

Speaking to the concept of building large ships, as can be afforded by the national economy and shipbuilding funding:

> "*In a major war at sea, we may find that our cost-effective peacetime strategy of concentrating on economies of scale has created a situation of "too many eggs in one basket." The loss of a DDG while conducting an independent offensive surface action becomes a loss of missile and air defense, antisubmarine warfare (ASW), and escort capacity to the fleet—as well as a highly skilled crew.*" (Kline, J.E.)

In a truly distributed maritime operations, each of these LMACC vessels has the primary mission above and a secondary warfare mission unique to that platform. Anti-submarine warfare (ASW) vessels, anti-air warfare vessels, and surface warfare vessels, for example, would be distributed among the Sea Fighter, and in company with Sea Hunter vessels as sensors. A "pack" might consist of four Sea Fighters and six Sea Hunters. Three packs would be employed forward and relieved on station by another three packs. This equates to 12 Sea Fighters and 18 Sea Hunters. The manned vessels would include a crew of 15 weapons and tactics specialists, commanded by an 03 or 04. The ship would be built around the current state of autonomy, which looks after the ship's well-being and navigates according to the rules of the road. As artificial intelligence and machine learning become more realistic for combat, these can be integrated into the LMACC. Trust in these systems will be generated by exercising capabilities in realistic contexts. Eventually it is possible that fully intelligent unmanned combat vessels may be ready, however that day is far off. The best perceptual and intuitive capability that exists is still a human brain. It can know when a vessel has exceeded the third level of control described at the beginning of this report and adjust to bring the system back to steady state.

Sea Fighter is currently being designed at Naval Postgraduate School, employing many innovative designs. For example, large ships have largely given up on maneuver as an element of defense against missiles. We are exploring the realm of "hyper maneuvering" tactics that are combined with kinetic, electronic and other forms of defense. For propulsion, diesel electric hybrid technology would be employed, potentially with water jet or screws that can leave one in trail for battery charging and energy cultivated from the movement of the ship in higher sea states. Weapons that have been proven rather than creating anew (until something better comes along) intelligent sensors, and C2 capabilities that allow it to communicate over the horizon in a satellite degraded/denied environment. Many tactics are taken from the aviation community, human systems integration, and the field of human-machine teaming.

Funding for this project was initiated under Navy Research Project funding, with N96 as its sponsor. To build this vessel (prototype) will take a stretch of the acquisition system, employing funding such as Joint Capability Technology Demonstrations (JCTDs), Congressional plus-up, and Other Transaction Authority (OTA) procurement. Nontraditional shipyards could be employed for this 1,000-ton, fully loaded vessel of less than 200 feet.

Our first design was based on an extension of the Cyclone coastal patrol (PC) class that could be refit using current autonomous seakeeping and mission behavior capabilities. Eventually the project employed a newly designed vessel, detailed in the project technical report. This partially manned vessel would perform most of its mission-state behaviors (e.g., sea keeping, maneuvering, systems maintenance) and mission behaviors (e.g., surface intelligence, surveillance, and reconnaissance; patrol of sea lanes; and intelligence gathering) autonomously, while the limited crew would perform oversight, man-in-the-loop and man-on-the-loop functions, as well as providing security. This would be an experimental but also CONOP developing system, one that could point the way to future ship/human teaming designs.

Findings and Conclusions

In our analysis, we have determined that the LMACC is a deterrent that can be effectively employed in denying our adversary a *fait accompli* from which the U.S. may not recover. LMACC is a forward deployed first island chain asset that includes human machine teaming onboard LMACC and between LMACC and accompanying Sea Hunter sensors.

The ability to create true distributed maritime operations is possible by having a primary mission across all vessels (long range surface to surface strike against terrestrial and surface targets) while distributing a secondary mission to each LMACC and Sea Hunters. A “pack” of this capability is 5 LMACC and 6 Sea Hunter. Deployment times of 60 days is anticipated, with a relief pack on station and the third pack undergoing maintenance. The cost of this entire capability of 15 LMACC and 18 Sea Hunter is less than the cost of a single guided missile destroyer (DDG). We also determined that CONOPS are feasible with the current capabilities, and most of the design features have already been incorporated into the current version of a prototype vessel for testing with Surface Development Squadron and Sea Hunter. However, additional work will be needed to create a more robust capability as the state of autonomy for said vessels is in infancy. Further development centers on mostly avoiding traffic in sea lanes. It also remains unlikely that autonomous vessels will possess striking capabilities.

In addition, this research produced several additional articles and theses content. One is a book chapter abstract which has been accepted but not yet published, on the principle of “emergence.” This explores the unanticipated actions of autonomy as real-world context changes (Gallup, S.P.) A second article investigates the funding costs and comparison with an *Arleigh Burke* class DDG. A third article by Mr. Ben DiDonato, and this PI was published in the Center for International Maritime Security. Fourth, an Acquisition Research paper was published.

There are also several related student theses in progress as well, particularly addressing communications to LMACC in an anti-access, area denial communications degraded environment.

Recommendations for Further Research

Our research shows that this vessel is completely within the capability of the United States military as we possess shipyards equipped for final development, and construction plans for the vessel are now being compiled. Future research should be focused on fully developing human machine teaming and human systems integration and brought to bear on a final design. In addition, war games at the Global and Pacific Fleet level need to incorporate the Lightly Manned Autonomous Combat Capability as a technical inject.

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NPS-20-N088-B: Incorporation of Operational Modeling Factors into Early Stage Ship Design via Digital Engineering

Researchers: Dr. Fotis Papoulias, Dr. Jarema Didoszak, Dr. Paul Beery, and Dr. Joseph Klamo
Student Participation: LT Allison Lenzi USN and CPT Aldin Sim (SG)

Project Summary

An operational analysis was conducted to inform the designs of future mine countermeasures (MCM) ships. This was primarily focused on identifying the ship design characteristics that will have the largest impact on mine detection and classification. The research developed a systems architecture, operational model, and related analysis to interpret results, draw conclusions, and make recommendations. An agent-based model was developed to simulate four different MCM scenarios in which an MCM surface vessel searched a designated area that contained 32 potential mines. For each of the four scenarios, ship design characteristics were varied to determine which variables had the greatest impact on performance. To determine how well each design performed, the data was analyzed against two different measures of effectiveness (MOE): the average number of mines accurately detected and classified (MOE #1) and the average number of timesteps required to achieve mission success (MOE #2). The study found that improving the ship speed and reducing the detection delay has a large impact on performance in the scenarios where there is no unmanned underwater vehicle (UUV) present. It also found that limiting the deployment range of the UUV is of paramount importance in the scenarios where there is a UUV present. In order to explore potential related trade-offs, a parametric mathematical model was developed. By conducting a sensitivity study of the MCM vessel design parameters and their effects on the operational capabilities of the vessel, several key parameters were identified. Such an approach can serve as the basis for a methodology influencing early-stage vessel design choices as dictated by mission operational requirements.

Keywords: *mine countermeasures, MCM, digital engineering, parametric models, operational analysis, early stage ship design*

Background

Naval architects have long struggled to design ships that find the delicate balance between stakeholders' desires and the fundamental requirements of physics. An example of an ongoing collaborative balance is between the Center for Innovation in Ship Design (CISD) at Naval Surface Warfare Center Carderock Division and the Naval Postgraduate School (NPS) Total Ship Systems Engineering (TSSE) Program. CISD conducts early stage ship design with their entry level engineers while the NPS TSSE program is comprised of naval officers who have previously served as ship operators, maintainers, and builders. These two groups have been working to establish a collaborative partnership with the aim of enhancing the Navy's ship design and engineering workforce. Both groups have developed specific skill sets that are needed in order to advance early-stage ship design practices using digital engineering. The long-term goal of this endeavor is to determine the overall impact in considering operational capability drivers early in the ship design process. It is expected that early incorporation of operational factors and an ability to interactively adapt the design based on operational inputs from experienced operators will produce a more robust and operationally sound product. This will reduce detailed design rework, shortening the overall design-acquisition timeline. First, we determine the operational mission requirements for a vessel. Ultimately, a detailed analysis must be conducted in order to establish which of these primary factors will most heavily impact the vessel hull, mechanical, and electrical design. A necessary step in this is the development of a lower-resolution mathematical model that captures the most important features of the system and can be used for rapid multiple studies. Areas which produce the highest expected benefit can then be studied utilizing higher fidelity and more time-consuming models. Such a hierarchical approach has the benefit of minimizing the time required for the insertion of operational modeling results into an early-stage design.

Findings and Conclusions

In order to provide a standard context, a scenario was set in a specific search area located in the Straits of Hormuz and was given moderate environmental operating conditions typical for the Middle East. The scenario modeling was conducted using an agent-based simulation program. In all scenarios a total of 32 mine-like contacts were in the search box, and the MCM surface vessel was provided a series of waypoints to guide its transit in conducting a strategic search to detect and classify the mine-like contacts. Several versions of the scenario were created varying the vessel type as well as several parameters of the search pattern inside the search box. The model varied the following: MCM ship speed, minimum detection range, maximum detection range, minimum classification range, maximum classification range, probability of success, detection delay, mine speed, and UUV speed. Once all simulation runs were complete, the data collected was analyzed. The overall conclusion from the data collected in the thesis is that there was no one specific set of design characteristics that resulted in excellent performance across all scenarios and both MOEs. However, when considering MOE #1 (number of mines detected and classified) and the scenario that did not include a UUV, the most important design factors were mine speed, sensor ranges, and ship speed. When the UUV was added, the most important characteristics became sensor ranges, detect delays, and probability of success. When considering MOE #2 and the non-UUV scenario, ship speed, detect delay, and probability of success were most important. The main takeaway is that a focus should be placed on improving the design of a dedicated MCM ship rather than one that relies on UUVs.

Based on the previous result, we decided to leverage the operational study insights and establish a relationship between several concrete and intuitive vessel design parameters such as length, displacement, payload, and range. Utilizing relationships between vessel volumetric Froude number and the admiralty coefficient for an extensive database of MCM vessels, we developed a mathematical model using speed, range, payload, and displacement. Through the selection of vessel input parameters and variables, the model can calculate a predicted displacement value, and a general relationship between the key operational performance parameters of the MCM vessel speed, range, and payload carrying capacity could be established. Further sensitivity analysis was conducted to understand the extent of the effects on displacement values and variable relationships. The intent of this analysis was to understand the effects of changing critical parameters such as cargo carrying multiplier, propulsion power weight density, and specific fuel consumption values. Suitable and realistic intervals were selected and varied, and a sensitivity ratio was calculated. The results indicated that fuel efficiency and speed selection appear to be some of the most sensitive variables, both from a physical design and operational considerations.

Recommendations for Further Research

Based on our results, the overall recommendation is to pursue design studies that include increasing ship speeds and sensor ranges for the non-unmanned underwater vehicle (UUV) type scenarios. Additionally, work toward developing a single system that is capable of detection, classification, and neutralization would be extremely beneficial as that could be an efficient future mine countermeasures (MCM) design concept. This is because the additional UUV system had a drastically negative impact on mission accomplishment times. Overall, the UUV scenarios did not perform exceptionally well when compared to the scenarios without them and they performed extremely poorly regarding measure of effectiveness #2 specifically. However, due to the inherent risks to human life associated with mine warfare, MCM systems that incorporate UUVs are still extremely relevant. Therefore, there is need for work in areas to study characteristics that impact UUVs' effectiveness so they can be leveraged to improve overall MCM mission performance. One recommendation in this area is to conduct similar research focusing on the logistics aspect of utilizing UUVs in MCM. Additionally, there is currently no comprehensive single system available or in development that is capable of detection, classification, and neutralization all in one. The results from this work indicated that the multi-system approach was not as effective the single system approach. Therefore, an alternative to improving the multi-system approach would be to begin work toward a first-of-its-kind comprehensive system that is able to achieve all the same objectives while also prioritizing human safety.

Regarding the mathematical model for the physical system, payload was defined to be the MCM module or system required for the MCM vessel to carry out its operational mission. In this aspect, the availability of payload weight is of paramount importance in order to relate its effects more accurately on displacement, speed, and range. There were no readily available weight data on specific MCM subsystems; therefore, the overall payload weight was estimated based on similar systems. This value could be further refined to get a better estimate as the MCM systems to be incorporated become known and their associated data is achieving higher fidelity. The model that was developed relied on a limited number of MCM vessel data points to establish a relationship between the MCM vessel length and its displacement.

The data points were selected based on the different available classes of MCM vessels and, thus, the applicability of the results is consistent with the number of data points available. A wider range of MCM vessel data points would significantly improve the robustness of the model by achieving better correlation equations that describe the relationships among the main design parameters and critical coefficients.

NPS-20-N096-A: NSW Lessons Learned Improvement (Continuation)

Researchers: Dr. Shelley Gallup and Dr. Curtis Blais
Student Participation: LCDR Brian Bird USNR and LT William Race USN

Project Summary
Lack of fit between NSWC needs for tacit and explicit knowledge and the system in place. Lack of knowledge among the lower level enlisted and junior officers about the LLP and how it could be used to assist. Single point of data entry and research of requests for information. Classified data only, difficult to obtain in the field. Lack of data aggregation across the many reports in the system. Using surrogate data from the Navy Safety Center of UNCLAS aircraft incident reports, several off the shelf systems were analyzed. Recommendations made to the sponsor. Next activity would include implementation plan, training and cross domain solutions allowing further distribution of knowledge across all of the NSWC operations ecosystem.

Keywords: *Knowledge Management, Lessons Learned, Semantic analysis, organizational change*

Background
At the beginning of this research, the LLP in its current state was analyzed using the Congruence Model for Organizational Fit, and data was obtained through interviews. Two thesis students, both from the special warfare community, continued the analysis of factors contributing to the lack of fit, and conducted interviews through various levels of the NSWC to determine what factors were responsible for low usage rates. As part of their effort, a Design Challenge event was planned, articulated to some 60 participants and ready to be conducted when COVID-19 travel restrictions were put into place. Information gathered to that point was treated qualitatively, plus work previously conducted the prior year by this researcher, were used to complete their thesis. That work treated causes and effects of low usage, but it did not answer the technical questions about how the platform needed to change in order to make lessons learned useful. A memorandum of understanding with the Navy Safety Center was then obtained, and a data set (very similar to lessons learned data) was provided. This allowed the researchers to consider commercial off the shelf resources that might fit with the needs of the NSWC. As a result, at least two contenders were specified, and a review of capabilities was conducted.

Findings and Conclusions
As stated in summary and findings above, the study concluded that there are many specific issues that are related to the information and knowledge platform. Loss of tacit knowledge is a problem, and the explicit knowledge (written) is a problem with turnover between teams and as personnel retire. The system needs to be distributed to the operational edge, which requires a cross domain solution. Personnel need to be able to obtain information from searches that are obtained through semantic AI solutions that compile

answers across many sources of information. These systems are common in the corporate environment and can be updated for use by NSWC. As those solutions are implemented, the organizational fit will again need to be analyzed and training will. need to be conducted.

Recommendations for Further Research

As the field of natural language processing, artificial intelligence and machine learning progress, the ability to archive and re-use knowledge that has been gained through tacit means and explicit documentation will become an important asset. In the area of special operations, it is very important that the lessons of the past become part of planning in the present, and critical research that reaches across stovepipes and organizations to improve lessons learned and knowledge sharing should be continued. Future research should be focused on adding knowledge and lessons to a cloud-based structure, available to all participants.

NPS-20-N113-B: Modeling and Simulation of Naval Directed Energy Weapons Engagements

Researcher: Dr. Bonnie Johnson

Student Participation: Ryan Kee CIV, Trevor Lutz CIV, Ernest Murray CIV, and Michael Schwitzing CIV

Project Summary

As the Navy moves forward with development and deployment of directed energy weapons (high energy lasers, railguns, and pulsed high powered microwaves), there is an urgent need for realistic modeling and simulation of directed energy engagements to understand their operational utility in concert with existing kinetic weapons and to understand the operational implications on limited shipboard energy resources. This project developed a realistic model to understand the power requirements and operational effectiveness of directed energy weapon systems on multiple escort ships working as a system of systems to protect a high value unit from inbound anti-ship cruise missiles in tactical fleet defense scenarios. The model represents the positions of each ship in the fleet and the geometry involved with target locations and vectors. In addition to developing directed energy tactics and concept-of-operations, the results of this modeling and simulation inform the Navy's understanding of environmental effects on directed energy weapons, the operational integration of directed energy weapons with kinetic weapons, shipboard integration requirements, and operational system of systems concepts.

Keywords: *directed energy weapons, shipboard integration, operational energy, modeling and simulation, systems of systems*

Background

Directed energy (DE) weapons offer advances to naval tactical operations with precise, speed-of-light, low cost per shot, adjustable lethality for various damage levels, and an unlimited magazine based on available electric power (Blau et al., 2018). DE weapons have the potential to improve surface ship layered defenses in conjunction with kinetic weapons by addressing close-in targets such as unmanned aerial vehicle (UAV) swarms, anti-ship cruise missiles (ASCM) and small fast attack ships. DE systems can also enhance situational awareness, battle damage assessment, and combat identification using their sensing capabilities. DE systems can provide "soft-kills", such as dazzling that can impair adversaries' sensors and weapon guidance capabilities, and "hard-kills" that destroy targets by burning through target materials.

The Navy conducted tests of the Laser Weapon System (LaWS) system that, in 2014, demonstrated that a DE weapon system can be successfully deployed and utilized in an operational maritime environment. LaWS used commercial off-the-shelf (COTS) fiber laser technology and operated at a power level of approximately 30kW. It was not fully integrated with ship power, cooling and combat systems and had limited beam quality. The Navy is developing newer DE weapon systems with power levels from 60kW to 500kW, significantly improved beam quality, and a variety of tactical capabilities. These systems include the Solid State Technology Maturation (SSL-TM), the Ruggedized High Energy Laser (RHEL), the Optical Dazzling Interdictor, Navy (ODIN), the Surface Navy Laser Weapon System (SNLWS) or High-Energy Laser with Integrated Optical Dazzler and Surveillance (HELIOS), and the High Energy Laser Counter-ASCM Program (HELCAP) (O'Rourke, 2019).

Several recent Naval Postgraduate School student-led research projects have contributed to the Navy's knowledge of DE weapon integration onto ships. A Systems Engineering Capstone team developed a systems architecture to integrate tactical energy information into a ship's combat system to inform warfighters making DE weapons engagements decisions (Rowney et al., 2017). This future capability is envisioned to allow warfighters to manage a ship's energy resources as engagement decisions are made. Another Systems Engineering Capstone team studied the operational utility of integrating DE weapon systems onto multiple ships in a naval strike group (Kuntz et al., 2017). A resident Systems Engineering thesis student modeled the energy storage needs of a DE weapon based on engaging different threats (Michnewich, 2018). His study included the impact of atmospheric conditions on the engagements. Additionally, a Systems Engineering Capstone team analyzed the ship placement and size, weight, power, and cooling (SWAP-C) considerations for integrating a DE weapon onto Landing Platform/Dock (LPD) 17 class ships (Liensdorf, 2018).

Findings and Conclusions

Through data and information gathering, systems and operational analysis, requirements development, and modeling and simulation, this project studied the naval shipboard energy needs of DE weapons in the maritime environment (Kee et al., 2020). The study produced a model of a fleet system of laser weapon systems and an analysis of their operational capability and energy needs against complex threats. This study's systems analysis method can be leveraged for future studies of integrating high-energy lasers as well as other weapon systems with significant energy needs onto naval ships.

This study informs N9's need to understand energy usage of DE weapons integrated onto naval ships. DE weapons have significant energy needs, which are highly dependent on the operational environment and individual tactical scenario. A DE weapon needs to impart "power in the bucket" (the amount of laser energy incident on the target) to its threats to make soft or hard kills. Additionally, the power must be sustained for a length of time (laser dwell time) to achieve lethality effects. A DE weapon's laser beam experiences thermal losses as the beam traverses the distance through the atmosphere to the target. Different atmospheric conditions cause different amounts of power loss. Thus, the ship must expend more energy to power a DE weapon for a longer period of dwell time depending on the type of threat (threat material thickness, composition), the threat proximity to the laser, and the atmospheric conditions. N9 must ensure that ships that are candidate hosts for future DE weapon systems can provide the energy necessary to effectively operate laser weapons against their intended threats.

This study developed a model and analytical method that supports the determination of the energy needs of a single DE weapon system aboard a naval ship as well as the energy needs of a multi-ship fleet system of laser systems (Kee et. al, 2020). The fleet model included deconfliction strategies to ensure that a laser on one ship doesn't accidentally fire at another ship in the fleet. The research team modeled a highly complex threat environment to estimate the DE weapon system energy usage in more extreme situations. This ensures that N9 can develop energy requirements for future ships that meet the needs of future DE weapons.

The study provided an understanding of the relationship between, and contribution of, DE weapon system factors that affect laser dwell time and power in the bucket calculations. The analysis of the model and simulation determined the relative contribution and importance of the DE weapon system factors, including atmospheric effects, laser characteristics, kill distance, and threat characteristics to the energy required. The analysis also calculated the associated cooling rate and heat dissipation required for DE weapon operations.

Recommendations for Further Research

This study lays the foundation for further research in the shipboard integration of directed energy (DE) weapon systems and other types of future weapon systems, such as the railgun and high-powered microwave (HPM) system. This study provides an analysis method and model for a fleetwide system of laser weapon systems. Other weapons, such as railguns and HPMs [MJCS1] can be added to the model. The model can also be used to study laser weapon defense against a variety of different threat scenarios. The Navy can continue to analyze the energy and cooling needs of these future weapon systems by updating the model with higher fidelity laser, threat, and scenario data. Model updates can include accounting for the physical geometry of ships in the fleet (refining friendly fire zones and addressing DE weapon field of view with respect to ship superstructure and heading); refining laser cycle times (to include cool down periods, target acquisition times, and turret slew times); adding resources (to model finite "magazines" of available power and cooling capability, exploring the effect of depleting these resources to overall fleet performance); and refining targets (increasing numbers of targets and modeling additional types of targets).

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NPS-20-N137-A: Impact on Naval Operations of Adopting JP5 as Single Fuel

Researchers: Dr. Geraldo Ferrer and Dr. Simon Veronneau
Student Participation: LCDR Dale Lessner USN, LCDR Edwin Jimenez USN, and LT John Walters USN

Project Summary

Inventory pooling, sometimes referred to as risk pooling, is a supply chain management technique used to mitigate demand uncertainty by consolidating stock points or reducing the variety of offered products. It is most beneficial where demand is varied and not positively correlated. If the demand for two products, in this case F-76 and JP-5, were pooled into demand for a single product under the SFC, the potential for lower demand for one product within a given time period may then offset the potentially higher demand for the second product. While the pooled demand under the SFC is calculated as the sum of the of the averages of the two formerly distinct products, the pooled variability of demand decreases (expressed as the standard deviation of the random variable), reducing the total inventory required for the same service level.

To define the maritime operational environment, the unclassified scenario developed for this study uses a fictitious conflict with the People's Republic of China (White House, 2017, p. 46). This scenario assumes increased CLF utilization by switching to the SFC in a contested environment. The order of battle modeled in this scenario was not based on actual military planning documents. Instead, we chose forces which represent typical combatant ship combinations, and known commodity usage rates, to determine the logistics necessary to maintain continuous combat operations.

The concept of operations chosen to provide the fuel logistics necessary for sustained combat operations is based on what the Center for Strategic and Budgetary Assessments termed "Go Big" (Walton et al., 2019, p. 41). Two scenarios were modeled using the same combatant composition. Scenario 1 represents the status quo of using two fuels, F-76 and JP-5. Scenario 2 uses only JP-5 to satisfy both aviation and ship propulsion fuel requirements. The scenarios demonstrate that fewer CLF and charter tankers are required to support the same operations under the SFC, providing an increase in task force endurance, compared with keeping different fuel types.

Keywords: *single fuel concept, SFC, Jet Propulsion-5, JP-5, Naval Distillate Fuel, F-76, fuel supply chain, combat logistics, afloat fuel inventory posture*

Background

In 1986, the United States and its NATO allies adopted a single fuel policy for all land-based operations selecting the JP-8 (also known as F-34) as its single fuel. That decision was not extended to maritime operations because of the low flashpoint (100F) of the JP-8, making it an onboard fire hazard. Just like the JP-8 was standardized as the fuel of choice for all land-based operations, the JP-5 has long been considered as the single fuel alternative for maritime operations. The US Navy uses JP-5 as the fuel of choice for all its aircraft because it has high flashpoint (low propensity for spontaneous ignition), with low risk of shipboard fire. On the other hand, US Navy uses F-76 in all shipboard propulsion and electric-generation conventional systems. The specifications of jet fuels, such as JP-5 and JP-8, are quite strict to match the engineering requirements of jet turbines. Shipboard propulsion, however, may use most varieties of kerosene or diesel oil. That makes JP-5 the natural choice to become the single fuel concept in naval operations.

However, adopting JP-5 as a single fuel raises a few challenges: although shipboard propulsion and electric generation systems can operate with a wide variety of fuels (including the JP-5), the F-76 has a small price advantage relative to JP-5: it has better lubricant properties and higher energy density. Consequently, the switch would necessarily increase direct variable costs, especially if vessels operating with JP-5 require lubricant additives. In addition, the F-76 is more widely distributed than the JP-5.

In this study, we examine whether the logistical benefits of selecting JP-5 as the single fuel concept overrides the direct cost increases created by adopting a more expensive fuel to power all assets during naval operations.

Findings and Conclusions

Both the USAF and U.S. Army came to adopt JP-8 as the single fuel on the battlefield due to separately encountered problems. The USAF had determined that JP-4, which has a low flashpoint, was unsafe and volatile for continued use in their aircraft. The Army experienced wax crystallization buildup at low temperatures in No. 2 diesel, which clogged fuel lines and caused engine failure in M-1 tanks. In 1990, the Army and USAF adopted JP-8 as the SFC on the battlefield, but the Navy abstained because of the flashpoint issue (Garrett, 1993). Despite skepticism of using JP-8 due to minor mechanical problems encountered by U.S. Army personnel, some advantages were observed on the battlefield such as increased survivability when USAF shifted from JP-4 to JP-8, and simplified fuel logistics when the U.S. Army converted to JP-8,as they used this oil for both M-1 and helicopters. Both branches achieved the DoD’s goal to simplify fuel logistics operations on the battlefield and interoperability within our military components including our NATO allies (Le Pera, 2005). However, the Navy could not adopt JP-8 because its flashpoint is too low to safely carry onboard ships.

There are a few potential impediments to adopt JP-5 as the naval SFC to be considered:

1. Engine Performance and Wear
2. Preventive Maintenance and Filtration
3. Copper Nickel Contamination

Many technical reports were written about engine wear, preventive maintenance and copper-nickel contamination related to SFC, and all of them concluded that the impact was minor or the SFC would improve engine performance (Tosh et al. (1992); Guimond (2007); Pogarty (2014); NF&L CFT (2018); Rebold (2004); NAVAIR (2006); Putnam (2018).

Inventory pooling, sometimes referred to as risk pooling, is a supply chain management technique used to mitigate demand uncertainty by consolidating stock points or reducing the variety of offered products. It is most beneficial where demand is varied and not positively correlated. If the demand for two products, in this case F-76 and JP-5, were pooled into demand for a single product under the SFC, the potential for lower demand for one product within a given time period may then offset the potentially higher demand for the second product. While the pooled demand under the SFC is calculated as the sum of the of the averages of the two formerly distinct products, the pooled variability of demand decreases (expressed as the standard deviation of the random variable), reducing the total inventory required for the same service level.

Unlike resupply to commercial facilities, which are often triggered by timed deliveries, CLF vessels onload at irregular intervals, and as often as practicable. A combatant and CLF may UNREP again after only two or three days, if the combatant received unexpected orders to travel to an area of operational responsibility without CLF coverage, and its next UNREP is unknown. Hence, the time between onloads for each product type is variable. Moreover, whereas a goal for commercial facilities is to reduce inventory while maintaining service level, DoN guidance mandates that CLF assets shall refill to their maximum allowable storage capacity as often as practicable. Thus, the reduction in standard deviation of demand during cycles may then be viewed as supplemental fuel brought into the battle space, and an increase in fuel autonomy. Stated differently, under the SFC, at any given time, this excess fuel may be viewed as longer operating range.

To define the maritime operational environment, the unclassified scenario developed for this study uses a fictitious conflict with the People's Republic of China (White House, 2017, p. 46). This scenario assumes increased CLF utilization by switching to the SFC in a contested environment. The order of battle modeled in this scenario was not based on actual military planning documents. Instead, we chose forces which represent typical combatant ship combinations, and known commodity usage rates, to determine the logistics necessary to maintain continuous combat operations.

The concept of operations chosen to provide the fuel logistics necessary for sustained combat operations is based on what the Center for Strategic and Budgetary Assessments termed "Go Big" (Walton et al., 2019, p. 41). Two scenarios were modeled using the same combatant composition. Scenario 1 represents the status quo of using two fuels, F-76 and JP-5. Scenario 2 uses only JP-5 to satisfy both aviation and ship propulsion fuel requirements. The scenarios demonstrate that fewer CLF and charter tankers are required to support the same operations under the SFC, providing an increase in task force endurance, compared with keeping different fuel types.

Recommendations for Further Research

This study did not address the impact on combatants themselves. Most engineering and technical specification concerns have been evaluated and would not prevent SFC implementation. Our central premise is that the SFC provides operational benefits by simplifying maritime fuel logistics and enhancing average battle group inventory posture. For most combatant platforms, the operational benefits stop at the increased flexibility of the CLF to meet combatant demand. For example, aircraft carriers use nuclear propulsion and therefore already only store JP-5 aboard, and while guided-missile cruisers and destroyers store both products, F-76 is stored in seawater-compensating tanks for ship stabilization purposes (NAVAIR, 2006). Thus, while it is mechanically possible to transfer fuel from an existing F-76 storage tank to the JP-5 service tank, this is procedurally forbidden for the sake of aircraft safety.

Amphibious platforms such as landing helicopter ships (LHA/LHD) and landing platform docks (LPD) are designed with ballast tanks in lieu of seawater-compensating tanks (NAVAIR, 2006) and therefore may be able to transfer fuel from F-76 storage to JP-5 service tanks, without sullying JP-5 for aviation use. Since these platforms have higher aviation fuel demand than other surface combatants, relative to ship propulsion fuel, their JP-5 storage capacities relative to F-76s are large. Therefore, amphibious platforms have the potential to experience the most significant benefits from SFC implementation.

Our preliminary analysis confirms this theory. We used our historical dataset and factored in previously unused fuel demand serviced by Defense Fuel Support Points and foreign sources under Acquisition and Cross Service Agreements. By observing the means and standard deviations of LHA/LHD and LPD demand for each fuel type were calculated, and applying the inventory pooling method, our cursory analysis showed a 6.17 percent storage capacity expansion for LHA/LHDs and 3.15 percent for LPDs. While these figures appear modest, two points should be noted: first, these figures already account for JP-5 reduced energy, and second, these figures include peacetime steaming and inter-theater transit fuel demand, which constitutes the bulk of F-76 usage. Therefore, the SFC may provide even greater benefits during MCOs with high aviation operational tempo. However, a detailed analysis is recommended to confirm that amphibious platforms would enjoy these benefits.

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NPS-20-N159-A: Non-Standard Navigational Methods for Unmanned Aerial Vehicles (UAV)

Researchers: Dr. Sean Kragelund, Mr. Aurelio Monarrez, and Dr. Isaac Kaminer
Student Participation: LT Andreina Rascon USN, ENS Benjamin Hogin USN, and LT Theodoros Tsatsanifos FORNATL GR

Project Summary

Unmanned aerial vehicles (UAVs) have become overwhelmingly reliant on the Global Positioning System (GPS). It is important to develop alternative navigation strategies when GPS is unavailable. Dead-reckoning techniques can integrate locally sensed inertial rates to estimate an aircraft's position and orientation, but navigation errors will eventually render these solutions unusable unless the vehicle can obtain external navigation fixes. This project investigates the feasibility of geomagnetic navigation for small UAV platforms. The study considers localization algorithms originally developed for underwater vehicles, as well as trajectory generation algorithms for exploiting features in a magnetic field map to obtain a navigation fix. Several of the necessary hardware and software components were ground tested using actual payloads and sensors for a representative aircraft. While unable to conduct flight tests, we conducted a limited experiment on Monterey Bay to collect a dataset with GPS, inertial, and magnetic sensors, and build a geomagnetic map for further study. We believe that geomagnetic localization has potential when GPS navigation is not possible; however, engineering challenges due to platform self-noise present an obstacle to its widespread implementation on small UAVs.

Keywords: *Global Positioning System (GPS), unmanned aerial vehicle, UAV, unmanned aerial system, UAS, inertial navigation, inertial measurement unit, IMU, geomagnetic navigation, magnetometer*

Background

The GPS is a key enabler for autonomous systems, and UAVs have become overwhelmingly reliant on this system for navigation. If GPS becomes unavailable for any reason, a human operator must typically abort the UAV's mission, assume remote control of the aircraft, and visually navigate using an onboard video camera. Dead-reckoning techniques can integrate locally sensed inertial rates to estimate an aircraft's position and orientation, but navigation errors will gradually accumulate and render these solutions unusable without external navigation fixes. As a result, there is considerable interest in alternative navigation techniques when a GPS fix is not possible.

The Navy Research Program funded two studies to investigate this topic in 2020, with different focus areas. Project NPS-20-N159-B assessed methods for integrating an inertial measurement unit (IMU) with an electro-optical camera to obtain external navigation fixes. Computer vision techniques extracted features from real-time video for correlation with prior maps of aerial imagery or models of the sun's position. For operations in "featureless" desert or open ocean environments, our project (NPS-20-N159-A) assessed the feasibility of geomagnetic navigation for unmanned aerial systems (UASs). This map-based localization technique is like terrain-aided navigation, but it uses a map of the earth's magnetic field instead of digital elevation or underwater bathymetry data (Tucker, 2020).

Geomagnetic navigation has already been demonstrated on autonomous underwater vehicles (Teixeira, F. C., Quintas, J., & Pascoal, A., 2017) using a commercially available underwater magnetometer with sensitivity of 0.02 nT (Marine Magnetics, n.d.). Other commercially available magnetometers with sensitivity of 0.0003 nT have been integrated on fixed-wing unmanned aircraft (Gordon, 2016) for survey applications. Having confirmed the feasibility of this approach, we investigated various estimation techniques described by Teixeira, F. C., Quintas, J., Maurya, P., & Pascoal, A. (2017) since Martins da Cruz (2019) concluded that particle filters outperformed both extended and unscented Kalman filters for underwater geomagnetic navigation.

During map-based navigation, a vehicle's trajectory impacts the accuracy of its estimation filter. Since errors in IMU-based position estimates grow with time, a vehicle must take periodic excursions from its intended route to visit magnetic anomalies that provide a map-based navigation fix. Therefore, geomagnetic navigation must plan and follow trajectories that strike a balance between exploiting the map and maximizing sensor accuracy. Cichella et al. (2018, 2020) describe real-time trajectory generation methods which can achieve this goal.

Findings and Conclusions

The scope of this study was bounded by current and foreseeable payloads, configurations, and interfaces for the ScanEagle Group II UAS operated by Naval Special Warfare (NSW). The researchers engaged representatives from the topic sponsor organization, NSW Group TEN, as well as Special Reconnaissance Team UAS operators and ScanEagle payload developers at Naval Information Warfare Center-Pacific (NIWC-Pac). Several NPS students also participated through classroom and project work.

During Winter Quarter 2020, the ME4811 Multivariable Control class developed optimal trajectory generation and path-following algorithms for the NPS ScanEagle's backseat driver. Students used MATLAB and Simulink software to a) identify ScanEagle turn rate characteristics; b) implement waypoint and trajectory generation algorithms; and c) design a path-following controller. Software-in-the-loop testing with the NPS backseat driver and the ScanEagle's ground control station verified that these algorithms were ready for flight testing. During Summer Quarter 2020, Dr. Isaac Kaminer taught the ME4821 Marine Navigation course using geomagnetic navigation as the example application. Since COVID-19 restrictions cancelled all this study's ScanEagle flight tests, our ME4821 student conducted an experiment on Monterey Bay to collect sensor data from a GPS receiver, a ScanEagle IMU, and an

Explorer magnetometer (Marine Magnetics, n.d.). The experiment validated the ScanEagle IMU's software interfaces, and we used this dataset to generate a magnetic map of the local area for geomagnetic navigation simulations.

This project also leveraged complementary software development tasks completed in support of other ScanEagle research at NPS. First, we procured a new ScanEagle payload from NIWC-Pac that combined an Ellipse-N IMU (SBG Systems, n.d.) and a Jetson TX2 computer (NVIDIA, n.d.) for running the NPS backseat driver architecture. New software implements two-way serial communication with the IMU, allowing in-flight magnetometer calibration and simulated GPS dropouts. Additional software provides real-time telemetry from the ScanEagle camera turret needed for new vision-based algorithms studied under NPS-20-N159-B. Optimal trajectory generation algorithms are implemented on the TX2 using Python open-source optimization libraries. Exploiting Python's multiprocessing library, we spawn a configurable number of optimization processes, each with a different initial guess. These processes run concurrently to fully leverage the TX2's six-core processor. When all optimizations have finished, or after a configurable timeout occurs, the best trajectory solution is forwarded to the path-following controller. This controller first generates waypoints needed to bring the aircraft to a desired initial condition, then generates closed loop turn rate commands to guide the ScanEagle along the optimal trajectory.

Although COVID-19 restrictions prevented our scheduled flight tests in 2020, the necessary hardware and software components were ground tested using actual ScanEagle payloads and sensors. We have high confidence in the inertial navigation, trajectory generation, and path-following methods investigated for this study. Moreover, the magnetic map generated from underwater magnetometer data will be adjusted to represent magnetic field measurements at typical ScanEagle flight altitudes. This will support further analysis, but additional testing is needed to determine whether the ScanEagle IMU's magnetic compass can detect features in geomagnetic maps produced from more sensitive magnetometers.

Recommendations for Further Research

This study assessed the feasibility of implementing geomagnetic navigation algorithms on a Group II unmanned aerial system (UAS) when the Global Positioning System (GPS) is unavailable. While highly sensitive magnetometers that meet the size, weight, and power constraints of a Group II UAS are commercially available, integrating these sensors onto an aircraft presents a significant engineering challenge. To avoid magnetic interference, highly sensitive magnetometers should be deployed at least two meters away from their host platform. For maximum sensitivity, aerial sensors are usually towed behind a fixed-wing aircraft or suspended below a rotary-wing aircraft. Although these types of magnetometers have been integrated on purpose-built aircraft, these solutions are impractical for addition to existing Group II UAS platforms. Therefore, we recommend that future research focus on methods for subtracting a platform's magnetic interference from an onboard magnetometer's measurements. This would allow a UAS to recover the true magnitude of Earth's magnetic field for navigation purposes. Specifically, future research should investigate whether machine learning approaches can address practical challenges of implementing geomagnetic navigation sensors and algorithms on small, unmanned aircraft.

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NPS-20-N159-B: Integrated IMU/EO-Sensor Navigation System for Aerial Vehicles

Researcher: Dr. Oleg Yakimenko
Student Participation: No students participated in this research project.

Project Summary

This study assessed feasibility of incorporating a data flow from an existing or add-on electro-optical sensor aboard a tactical unmanned aerial system (UAS) as a navigational aid in lieu of the missing position fix updates typically provided by the Global Navigation Satellite System (GNSS). It presented the overall concept, discussed imagery data that is typically available (including that provided by the topic sponsor), assessed the architecture of a GNSS-free navigation system, and presented trade-off trials on evaluating potential performance of the integrated vision-based navigation system. These evaluations allow to better understand the relationship between specifications and quality / feasibility of navigation solution and determine the effectiveness of different approaches of utilizing a video stream for short-term navigation solution to proceed with / complete UAS mission and return to the base.

Keywords: *UAS, GPS-denied navigation, EO sensor, navigational aid, feature extraction and matching, vision odometry*

Background

In recent years, the navigation system of the vast majority of surface, ground, and aerial vehicles has become heavily reliant on the updates received with help of the Global Positioning System (GPS) and other Global Navigation Satellite Systems (GNSS). Combined with the high-rate outputs from the Inertial Navigational System (INS), the integrated INS/GPS provides positioning, navigation, and timing (PNT) services on a global or regional basis and can deliver less than 1-meter accuracy of determining a vehicle's position with respect to the surface of the Earth while also contributing to a more accurate estimation of an attitude (for large vehicles). Operating in a GPS-degraded/denied environment leaves the standard INS to be the only source of the vehicle's movement estimation that eventually causes a substantial degradation of vehicle capabilities. That is why there is an interest to use alternative sources to sense the vehicle's movement and rotation along with INS or even with INS/GPS. This is especially true for autonomous vehicles.

Luckily, these days, autonomous vehicles are commonly equipped with a variety of miniature passive sensors providing situational awareness. Some of these sensors can also be used to enhance the vehicle's pose (position and attitude) estimation. The Earth's magnetic field, position of the sun, and even the ground-sky temperature gradient are some of the environmental cues that have been leveraged for navigation purposes. In situations when a vehicle is equipped with a vision-based system, optical sensors can naturally be used as a navigation aid as well. Using computer vision to support a variety of the navigation tasks for autonomous vehicles is a rapidly growing area of development. There is a huge body of literature describing different approaches to utilize simultaneous localization and mapping, especially for indoor vehicles.

While vision-based navigation is not possible in all weather and lighting conditions, it still offers a viable alternative and GPS backup when available, especially for the Intelligence, Surveillance, Reconnaissance (ISR) missions conducted by Unmanned Aerial Systems (UAS) can probably benefit from the vision-based navigational aids (NAVAID) the most. While modern INS becomes more robust to individual GPS spoofing, it is unclear whether it can provide a no-aid (IMU-only) short-term (tens of minutes up to an hour) navigation solution accurate enough to proceed with / complete the mission and / or return to the base safely in the case of operating in the GNSS-denied environment or challenging conditions, e.g. urban canyons.

Findings and Conclusions

This study explored a capability to use video data to enhance navigational accuracy in the case a GPS signal is absent or degraded or spoofed.

The approach used in this study was based on analyzing samples of video data available from the previous test trials of a small tactical UAS if similar video data collected using different EO data sources just for this research effort. This analysis included evaluation of data completeness, quality, and usefulness for obtaining the navigational fixes in a series of offline tradeoffs.

The key findings are as follows: 1) Using the existing EO sensors (with a video resolution of 640pix-by-480pix) allows to effectively employ the existing computer-vision algorithms to provide visual odometry and navigational position aids. 2) The number of feature points provided by such algorithms as ORB and Speeded-Up Robust Features (SURF) is sufficient even if flying low over a feature-poor terrain. 3) While the number of matched pair points drops with the decrease of the sampling rate, it is fair to expect the NAVAID update rate of up to 1 Hz. 4) Implementation of the vision odometry within the integrated navigational system implies availability of the UAS and gimbal states. Only then a full 3-D solution can be obtained. Visual odometry while executing simple maneuvers, like a straight level flight or coordinated turn, may be conducted with a limited state information if the gimbal settings are fixed. 5) The heading NAVAID can be obtained executing a coordinated turn maneuver capturing the area in the close vicinity of the expected sun location. This could help UAS to safely navigate towards the base where command and control link could be reinstalled.

Recommendations for Further Research

Further development would involve: 1) Obtaining a complete set of data (video and INS/GPS telemetry) from the UAS in question. 2) Tuning the visual odometry algorithms to match true data provided by the INS/GPS. 3) Conducting representative GPS-failure scenarios and verifying the architecture of inclusion of visual odometry data into the integrated navigation solution

NPS-20-N190-A: Added Capability in RASP

Researchers: Mr. Alan Howard and Mr. Brandon Naylor

Student Participation: No students participated in this research project.

Project Summary

This project originally set out to determine ways to improve the Replenishment at Sea Planner (RASP) tool, by improving the code and user experience, but the research team later pivoted towards improvements to RASP that could allow it to serve multiple purposes. The RASP developers suggested that it could be used to not only optimize our own logistics planning, but if reconfigured, could also be used to model our adversaries' logistics and power projection capabilities. Based on further guidance from the topic sponsor and RASP development team, this study then pivoted towards informing the development of Red RASP, which models the capabilities of China's People Liberation Army Navy (PLAN) to resupply their ships operating throughout the South China Sea region and beyond. In our modeling, the US Navy combatants and resupply ships in Red RASP were replaced with notional versions of PLAN ships and tankers, and extra ports were added along China's coast to reflect the greater availability of home ports available to the PLAN. An ongoing parallel study is scheduled for completion in FY2021, using the Red RASP model to draw conclusions regarding the PLAN's power projection capabilities.

Keywords: *RASP, Replenishment at Sea Planner, logistics, modeling, adversary capabilities, South China Sea, China, power projection*

Background

RASP is a modeling tool developed at the Naval Postgraduate School (NPS) that is used by the Military Sealift Command (MSC) to optimize the schedules of oilers and replenishment ships used to resupply combatant ships while at sea. The model optimizes schedules based on cost and ship availability when planners are given a known schedule for resupplying needs of combatant ships. This project originally set out to improve the tool's functionality and interface with the MSC in mind as the end user, but we later received guidance that our efforts would be better spent finding alternative uses for RASP. While the developers had the task of improving the tool for use in the MSC fully covered, one area of research they had identified, but hadn't been able to explore, was using RASP to model our adversaries' capabilities. Although the funds provided by the Naval Research Program (NRP) could not be used for modeling adversary capabilities in RASP, it was determined they could be used to fund the background research into an adversary's fleet composition and capabilities, which would inform the development of the model. A parallel effort was already funded for the Energy Academic Group at NPS to contribute towards RASP-related development, which allowed the research conducted under this NRP effort to inform the development of new RASP tool used to model adversary capabilities, dubbed Red RASP.

Findings and Conclusions

Although the types of funds provided by NRP could not be used to fund development or modeling efforts using Red RASP, we were able to research China's capabilities to compile the data that would be fed into the model in a separately funded effort. Combined, these efforts will help paint a better picture of our adversaries' capabilities to inform fleet readiness decisions. Naval research databases such as Jane's (2020) were searched to gain information regarding the PLAN's fleet composition and ship characteristics. It was determined that China does not currently possess enough military tanker ships to support long-range power projection beyond the coastline of China and nearby nations where they own significant port infrastructure. However, their reach is not limited to the coast of China, because of their extensive investments in infrastructure in other nations in the Pacific and along the Indian Ocean. Although these ports China has built in developing nations are not dedicated explicitly towards military use, it is reasonable to expect that they would aid the PLAN during any conflict, because they are mainly Chinese owned and operated. The same applies to a vast fleet of commercial tankers; even though they are owned by Chinese businesses, the government of China has the necessary influence to redirect these businesses to support military interests. They have already done this with their fishing industry fleet in asserting control of legally contested waters in the South China Sea.

Recommendations for Further Research

Future work remains in using the Red Replenishment at Sea Planner (RASP) model to predict China's and/or other adversaries' capabilities, as the scope of this project was limited to researching adversary assets to inform the development of the Red RASP model. Further work also remains in determining the impact that using commercial tankers and ports would have on our adversaries', particularly China's, reach and power projection, since a significant number of assets are controlled by state-owned corporations. Regarding added capabilities from commercial assets, questions also remain as to how much time is needed to adapt these assets to support military operations. These are questions that will continue to evolve in the coming years as China puts more emphasis on power projection, building thirsty aircraft carriers, and purchase of controlling interests in ever more foreign shipping and oil companies.

NPS-20-N208-A: Modeling Trust and Risk in USV Operations

Researcher: Dr. Moshe Kress
Student Participation: No students participated in this research project.

Project Summary
The adoption of new and advanced technologies takes time and effort, mostly because potential users of such technologies need to build trust in the systems built around those technologies. Unmanned Surface Vehicles (USVs) are such systems, and they play an important role in potentially future conflicts, which necessitate the study of trust in the context of those systems. In this research, we develop a methodology for measuring and monitoring trust, by connecting two factors that affect trust: (1) in-context risk factors related to the systems' components, missions and scenarios, and (2) mission-dependent cost of failure, to obtain a measure for the level of trust in employing USVs. Measuring trust can inform decision makers about the perception of relevant populations about the effect of possible mission-failure, and its cost, on their disposition regarding the deployment and employment of USVs. For example, one would possibly be able to classify group of people according to their scenario- and mission-dependent propensity to trust USVs. Also, the responses could identify USVs' functional areas, which are critical for building trust in given scenarios and missions. We use the Likert Scale to measure levels of risk, cost and trust, and suggest standard methods from experimental design and statistics, to evaluate the aforementioned connection.

Keywords: *Likert Scale, measure of risk, MOR, measure of trust, MOT, Unmanned Surface Vehicles, USVs*

Background
Many relations, processes and transactions in life depend on trust among people, and between people and entities, such as machines, computers and information sources. The topic of trust has attracted much attention in the academic world and generated a large body of research. The large diversity of research disciplines dealing with trust has resulted in many definitions for this term, not all of which are consistent. We will use a variant of a definition commonly used in the automation /robot community: *the belief that a system will help achieve mission's objectives in a scenario characterized by uncertainty and risk.*

As the DoD moves toward increasing levels of automation and autonomy among defense systems (Winnefeld, 2011) a move that means less operators responsible for operating and supervising more numerous and complex systems, the issue of trust becomes crucial: human decision makers and operators will be reluctant to utilize systems based on new and advanced technologies if they do not trust them. To operate such systems effectively, operators need to be able to correctly observe the cues these systems transmit to them, properly understand their meaning, and most of all, rely on the systems to perform fault-free as planned, and respond correctly to contingencies. However, automated systems in general, and autonomous systems, are prone to failures and errors (Manzey, 2012) and therefore, may not always respond as expected. The reasons for errors range from faulty physical designs and bugs in software to unexpected operational circumstances not planned for in the system's design. These possible failures, and the damage and cost they may incur, ultimately affect trust in said systems.

Findings and Conclusions

The primary contributions of this research are (1) studying the effect of systems' malfunctions and the cost of such failures on the level of trust, (2) developing a formal method, based on Likert scales, for measuring and monitoring the level of trust in USVs.

The basic idea of the *Measure of Trust* (MOT) is similar to the idea of utility in *economics* in that it incorporates uncertainty (risk) and cost (or reward) to determine individual's attitude towards a certain choice of action (e.g., employing USVs). Trust evolves over time and so is the MOT that measures it. Initially it only reflects the trustor's perception or belief regarding the risk and possible cost of employing the USV. Later, as the trustor starts accumulating operational experience, the MOT increasingly relies on actual performance of the USV. The MOT hinges on the individual's responses to two types of *risks* – technical and operational – and on his perception of operational *cost*.

An important term used in defining the MOT of a USV (or any system) is *functional area* (FA). An FA is a subsystem of the USV responsible for some specific functions or actions. Examples of FAs are vehicle control, propulsion, sensing, communication, firing, etc. Any FA is subject to failure or a cause for an error and malfunction. Depending on its severity, a failure in a certain FA may abort the mission and thus cause operational cost. Ideally, there would be a FA-based probability model that will combine the technical and operational risks into a single measure of risk (MOR). In reality, such an "engineering" approach would not be practical for evaluating the MOT because of lack of hard data and the unnecessary computational burden that such approach entails. Instead, we propose an approach based on an ordinal scale – the Likert scale (Joshi et al., 2015).

Recommendations for Further Research

The next stage of this research is implementation, wherein relevant personnel (operators, mission planners, commanders) will be asked to respond to a questionnaire described in the research report. Using experimental design and standard statistical techniques, the responses will generate an estimate for the function M described in the full research report. This function, which may vary among relevant populations, will identify key factors affecting trust in USVs, and thus will help developing better techniques and procedures for assimilating USVs in the force.

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NPS-20-N303-A: Human-Unmanned Teaming in Distributed Maritime Operations (Continuation)

Researchers: Dr. Mark Nissen and Dr. Shelley Gallup
Student Participation: No students participated in this research project.

Project Summary
The technologic capabilities of autonomous systems continue to accelerate, and teams of autonomous systems and people are becoming increasingly important, particularly where distributed maritime operations (DMO) are concerned. Computational experimentation offers unmatched, yet largely unexplored potential to address DMO research questions, and we employ the POWer computational environment to model and simulate DMO organizations and phenomena. We begin by building upon prior research to establish a baseline model for comparison. Then we adapt such model to represent DMO, and we compare key results to elucidate important insights into both the potential and difficulty associated with DMO.

Keywords: a*utonomous systems, simulation, combatant sensor integration, distributed maritime operations*

Background
This project expands on the prior year's efforts to understand the future trajectories of human and unmanned systems teaming. We understand how key it is for available manned and unmanned, surface and air, combatants, and sensors to integrate and serve as a cohesive, networked force, despite their distribution through physical space-time. We understand also how some aspects of contemporary command and control (C2) will require adaptation to accommodate DMO, along with how robust the POWer model is to novel concepts, such as DMO. Hence, we've identified several C2 adaptations and computational model elements to compose into a DMO model. Additional research is required to flesh out incomplete and emerging details of DMO.

POWer represents the state of the art in terms of organization modeling and simulation. We outline the research method centered on computational experimentation, which supports incredible internal validity and supplies experimentation power unavailable through other methods. Building upon our prior work, we model, simulate and analyze maritime operations as they are conducted today, with a particular focus on both manned and unmanned aircraft intelligence, surveillance and reconnaissance (ISR) missions. This establishes a baseline for comparison with one or more alternate DMO organizations conducting ISR missions. It also establishes a baseline for comparison with other missions (e.g., strike, air defense, surface warfare).

Findings and Conclusions
We adapt the contemporary baseline model above to reflect the DMO environment. Such adaptation

considers lines of effort from A Design for Maintaining Maritime Superiority 2.0 (Richardson, 2018) and the concept distributed lethality from Surface Force Strategy (Rowden, 2016) to flesh out DMO with some important detail. Specifically, we consider that one of the destroyers (along with its unmanned aircraft systems) in a strike group formation is assigned a geographically remote and organizationally separate mission. This involves some novel coordination, in addition to considerable complexity and stress for the strike group, which is required to accomplish its same mission without support from the breakaway destroyer.

Using POWer, we examine comparative strike group performance through simulation of the same ISR mission via current and DMO configurations. For each simulation, the model is run 50 times to examine varying conditions via Monte Carlo techniques, and comparative performance is gauged via seven key performance measures. Succinctly, the DMO configuration increases ISR mission duration by nearly 25%, and it adds to both the rework of mistakes and coordination load within the strike group. Alternatively, shifting to DMO has negligible effect on wait time, functional or mission risk. Maximum backlog, however, increases roughly fourfold, as requirements aboard the carrier and both destroyers pile up. Higher backlogs can lead to increased rework, coordination and wait time, as important information is not disseminated, and key decisions are not made in time.

Thus, we provide some novel insight and unique quantification of DMO impacts to the strike group stemming from a breakaway destroyer in the context of an ISR mission. Through examination of the areas of increased complexity and stress, experienced people can begin to assess the root causes and start outlining approaches to obviate or at least mitigate performance degradation.

Toward this end, we offer three suggestions. First, complexity and uncertainty are higher in a DMO configuration than the strike group baseline, and organization experience is necessarily considerably lower as well. These combine to complicate and stress the mission. One key approach to obviation or at least mitigation is practice: realistic testing through large scale exercises should be made a priority.

Second, the increased complexity and stress faced by a strike group in DMO configuration may be eased somewhat through anticipation and augmented staffing. Several additional people may be added across the key strike group ships (especially the carrier and destroyers) to step in and assist in DMO specific ways whenever one or more ships break away for geographically remote and organizationally separate missions.

Third, technology plays a role, specifically: the more that ships, commands and crews can understand their situations; receive and utilize timely, actionable knowledge and information; and coordinate their activities across ships, times and locations; the better their individual and collective performance. This requires a robust, reliable and extensible network that can perform well under conditions of degraded communication (e.g., sans satellites) as well as ideal conditions.

Recommendations for Further Research

One or more follow on studies can examine this same DMO configuration, but with a broader mix of manned and unmanned vehicles (e.g., Degree 0 through 5 autonomy). They can also examine conditions of reciprocal and integrated interdependence, to delve into the details of manned-unmanned teaming for DMO. Incorporating manned and unmanned surface and subservice vehicles into the configuration also offers potential to expand the analysis, as does adaptation to consider strike and other missions beyond ISR. These represent exciting future research studies, ones that offer great potential to inform our DMO thinking. All we need is time, talent and funding to complete them.

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NPS-20-N342-A: Modeling the Operational Value of Data Fusion on ASW and Other Missions

Researchers: CAPT Scot Miller USN Ret., Mr. Curtis Blais, and Mr. John Green
Student Participation: No students participated in this research project.

Project Summary

The Naval Air Systems Command Mission Engineering and Analysis Department (MEAD) conducts an annual cycle of engineering and mission-level modeling to support investment decisions for its OPNAV-98 sponsor. The Navy is integrating the Minotaur data fusion system onto the P-8A Poseidon maritime patrol aircraft and MH-60R Seahawk maritime helicopter to generate a comprehensive, shared, networked picture, offering increases in speed, accuracy, and memory capacity over legacy and manual data fusion systems. However, fusion influences on mission effectiveness are unclear since existing simulations do not quantify explicitly the impact of "better" data fusion. This study investigated a modeling, simulation, and analysis approach for quantifying the operational effectiveness of such systems. The working hypothesis was that fusion systems add value by improving situation awareness while reducing classification and identification times.

The research team constructed a small surface warfare vignette with a P-8 baseline and an excursion with a P-8 equipped with Sensor M, a Minotaur equivalent to determine if the surface picture is enhanced in both speed and quality when using the P-8M. From this effort, we developed detailed instructions on how to construct models that represent fusion processes. While the research team did not complete a coordinated anti-submarine warfare (ASW) vignette, we suspect that Sensor M would have made both ASW platforms, the Poseidon and the Seahawk, more responsive in such a challenging scenario, improving their ASW efficiency and effectiveness. Improving the surface picture often helps operators eliminate possible noise sources in the underwater environment faster. We recommend future efforts should focus on modeling the potential of integrating big data, cloud, and knowledge representation techniques to fully understand the added value of any one fusion/data analytic technique.

Keywords: *Minotaur, modeling and simulation, Navy Analytic Agenda, fusion; Naval Simulation System, NSS, advanced framework for simulation, integration and modeling, AFSIM*

Background

Our foundational hypothesis was that systems such as Minotaur add value by improving SA accuracy while reducing the amount of time to classify and identify contacts of interest. This improvement should have a significant effect on surface targeting, self-preservation, and coordinated antisubmarine warfare (ASW) operations. Minotaur does not fuse/correlate ASW sensors, so it has less direct ASW value, but remains useful in secondary ways, since ASW is dependent on a reliable surface picture.

The researchers expected few research challenges because NSS was designed from its beginning in the mid-1990s to evaluate situation awareness qualities. It emerged, though, that little in the way of mission-level fusion modeling has been performed in NSS, or any other common mission model. Further, fusion is a tricky subject, with poorly defined constraints and assumptions.

We explored trying to model the fusion process explicitly within NSS, but there was insufficient fidelity to support that approach. Instead, we had to determine the effects of fusion, then adjust the input parameters to see those effects emerge. We continuously validated this approach through reviews of other techniques, NSS subject matter expert interaction, and with the sponsors.

NSS was designed to explore questions of communications, command and control, and situation awareness. NSS has default selections of perfect situation awareness and communications, but also provides robust capabilities to explore what happens in warfighting scenarios when awareness is degraded. NSS developed some data processing architecture options that allow information from multiple sensors to be "fused" in various ways inside a platform or command center.

Whereas NSS has a fixed set of capabilities, advanced framework for simulation, integration and modeling (AFSIM) is a more modern simulation software architecture and provides users with considerable leeway in developing specific models of interest. It has a sizable and growing user community, offering opportunity to reuse products from prior development projects. Unlike NSS, though, AFSIM is a framework, having particular starting capabilities upon which particular simulation capabilities can be added. Unless an organization is going to reuse a set of developed capabilities and scenarios for several years on multiple projects, it may not be as cost and time effective as a fully functioning simulation such as NSS.

Findings and Conclusions

The researchers started with a literature review; discussions with experts in the fusion, Poseidon, and Seahawk communities; and investigation of various modeling tools (emphasizing NSS and AFSIM since those are available to the sponsor's organization). Fusion is a sophisticated process, fraught with misunderstanding. It is based on sound mathematics; however, those calculi work properly in a narrow-defined range of constraints and assumptions. Just as in actual operations, failure to attend to those in modeling will result in non-appropriate conclusions. NSS enables the exploration of command and control, situation awareness, and differing data architectures, so it has relevant capabilities. With NSS available on our server, we completed an NSS class and built unclassified practice scenarios to investigate fusion modeling techniques.

The goal was to provide MEAD with insight into how Minotaur, or other fusion systems, could be characterized in a mission-level analysis. We focused the research to deliver a description of how various available (but rarely used) NSS modeling techniques create the effects derived from airborne fusion systems. This description complements the NSS Analyst's Guide. As NAVAIR modelers employ this approach, their understanding of modeling various fusion systems will grow. Fusion and mission modeling are well explored research areas. Our contribution was not in inventing anything new but recognizing that the original NSS design considered the need for such capabilities, but no one had needed their use in the past two decades.

AFSIM shows promise but requires particular modeling expertise, with some "assembly" by the user. While shared plug-ins and libraries exist, each user has a different approach to modeling fidelity, so intermixing components can lead to misaligned logic. AFSIM has the potential to explicitly model actual fusion algorithms, a big plus for the NAVAIR analytic community. Continued exploration is warranted.

The fusion supplement gives practical modeling advice in several areas. While specific to NSS, this would apply to most models.

- Establish special signatures on platforms of interest that align with sensors of interest intended for use on the air platform. For instance, we assigned merchants ships an AIS "signature," then gave the P-8 an AIS "sensor."
- Consider sensor range settings and whether a sensor can detect, classify, or identify a given target. Often in fusion it takes multiple sensors to achieve detection, identification, and classification.
- Build a data architecture for each platform and command and control structure. In our case, we simulated manual fusion by forcing a senor signal through a pre-fusion data processing node, where various delays and errors could be introduced that represent real situations. If needed, many pre-fusion and fusion nodes can be chained together.
- Consider platform tactics based on the effects that fusion will have on the mission commander's thought process. It may not be intuitive.

This research focused on air platforms. Different approaches might be needed for other platform types. This research considered five kinds of sensors. Adding other sensors might add unusual complexity. We considered fusion systems working on a particular platform. Some fusion systems can fuse between platforms, raising new questions.

Recommendations for Further Research

The Naval Air Systems Command (NAVAIR) Mission Engineering and Analysis Department (MEAD, AIR-4.0M) conducts an annual cycle of engineering, engagement, and mission-level modeling to support investment decisions for their OPNAV-98 sponsor. There is interest in data fusion systems, such as Minotaur. The Navy is integrating Minotaur onto the P-8A Poseidon maritime patrol aircraft and MH-60R Seahawk maritime helicopter. Minotaur integrates sensors from Poseidon and Seahawk into a comprehensive, shared, networked picture, offering potential increases in speed, accuracy, and memory capacity over legacy and manual data fusion systems.

Fusion influences on mission effectiveness are unclear since the impact of "better" data fusion is not readily captured within existing MEAD simulations. The purpose of this study was to describe a modeling, simulation, and analysis approach for quantifying the operational effectiveness of such systems.

The working hypothesis was that fusion systems add value by improving situation awareness while reducing classification and identification times.

The researchers explored two models, the Advanced Framework for Simulation, Integration, and Modeling (AFSIM) and the Naval Simulation System (NSS). Due primarily to availability of the product to MEAD modelers and Naval Postgraduate School (NPS) researchers, the team focused on NSS, taking an introductory course, referencing its various manuals, and investigating scenario construction.
The research team constructed a small surface warfare vignette with a P-8 baseline and an excursion with a P-8 equipped with "Sensor M," a Minotaur equivalent. From this effort we developed a fusion modeling supplement to assist the MEAD modelers, with detailed instructions on how to represent fusion processes for airborne data fusion platforms.

Specific Recommendation 1: We recommend that NAVAIR modelers use the supplement to model Minotaur, with the NPS-developed unclassified scenario as a starting point. Provide constructive feedback to the researchers so they can adjust and improve the supplement.

Specific Recommendation 2: Once comfortable with the approach, we recommend NAVAIR modelers expand their fusion modeling to other platforms, such as Triton, which seems ripe for onboard fusion. Besides new platforms, modelers should try representing new sensors, such as a computer vision tool like the Office of Naval Research Surveillance, Persistent Observation and Track Recognition capability, which will introduce the team to fusion and to artificial intelligence-based data requirements, another soon-to-emerge modeling challenge. By this stage, the NAVAIR modeling team would be ready to discuss their work with the NAVAIR Fusion team and share best practices.

Specific Recommendation 3: We recommend that continued research be funded on using AFSIM to explicitly model fusion algorithms. This helps the analysists understand the true nature of the constraints and assumptions often employed in fusion.

General Recommendation: NAVAIR's concern about modeling fusion ought to be just the start. Based on other Navy research, NAVAIR should expect several more fusion and data-rich challenges to emerge from Big Data, machine learning, and explainable artificial intelligence techniques. Technologists will yearn to install these on aircraft; NAVAIR should be equally prepared to make investment tradeoffs on these options.

U.S. Fleet Forces Command (USFF)

NPS-20-N059-B: Teach RADARs to Communicate

Researcher: Dr. Ric Romero
Student Participation: LT Christopher Liu USN

Project Summary
The objective of this work was to investigate how an existing radar system could be configured to also

function as a communications system. Moreover, the goal was to ensure that both systems could operate at the same time. To that end, it was also our objective not to degrade the radar detection performance due to the interference that might result due to the addition of the communications function.

In this project, we proposed a feasibility study on how to embed low-power communications waveform into two common waveforms used by radar systems. Two types of radar waveform were investigated: pulsed waveform and a continuous wave (CW) linear frequency modulation (LFM) waveform. Quaternary phase-shift keying (QPSK) was used as the embedded communications waveform.

As a result, communications receivers were needed and proposed, and two receiver demodulator schemes were designed. The first one involved estimation of radar waveform parameters and the use of a traditional detector called maximum likelihood detection (MLD). The other utilized machine learning via deep neural network (DNN).

This project showed that it was feasible to inject low-power communications waveform into a legacy radar system; it also showed that good symbol error rates (SER) could be maintained for the communications while minimizing effect to the radar's detection performance.

Keywords: *radar, communications systems, waveform, symbol error rate, detection, probability of detection, estimation, machine learning, deep neural network, DNN, LFM, QPSK, SER, CW, RF, FPGA, RCR, SRBR*

Background

Communications systems (such as radios, telemetry, data links, etc.) and radars, despite having different purposes, are very similar in several ways. Indeed, radars were invented after observations of reflected radio waves from various objects such as passing ships at sea. Unlike a communications system, which only travels from a transmitter to an intended receiver at some certain distance, a radar waveform has to travel from the radar's transmitter, gets reflected by a target of interest, and returns backscatter to the radar's receiver. Due to the significant two-way path loss attenuation, a radar's power output is usually high.

Both radars and communications systems upconvert a waveform onto a carrier frequency that is conducive to some antenna size. In other words, radars can potentially be used as communications systems. There are indeed some studies suggesting it is possible and implementable (Meager et al., 2016). Several of these studies concentrate on radar-communications co-design. In other words, design of new radar and radio waveforms are proposed to build new systems capable of allowing both waveforms to function alongside each other. Such approaches are obviously costly since brand new systems will have to be designed and built.

Our goal in this is study is to actually look into "teaching," supplementing, complementing, or even designing the communications capability into existing radar systems or future versions using the same existing radio frequency (RF) transceiver. To that end, we propose to embed low-power communications waveform into two common waveforms used by radar systems. The waveforms are: pulsed waveform and LFM waveform; in terms of communications waveform, QPSK is proposed.

To complete the feasibility study, we propose communications receivers and investigate two receiver demodulator schemes. The first one involves maximum likelihood estimation (MLE) of radar waveform parameters and the use of traditional detection called MLD. The other approach as mentioned earlier uses DNN.

Findings and Conclusions

Purpose: The main objective of this work is to perform a feasibility study of "teaching" or configuring existing commercial or military radars to function as communications systems and perhaps to configure radar receivers to function as communications receivers. The idea is to use existing commercial or military radars to be technology multipliers—i.e., the next iteration of existing radar design can be potentially configured to be dual-function systems. In other words, there will be no need to build new RF front-end, and only re-programming of the digital portion of the radar is needed. Perhaps, even old legacy radars can be configured as such.

Methodology: Our research work plan includes the following steps: a) literature review on the subject including the ones by NPS Cognitive Sensing, Radio, and Radar (CSR2) laboratory; b) identify one or two radar systems (or waveforms) that may be usable for our feasibility study; c) develop signal modeling and analyses for the radar-embedded communications waveforms; and d) use RF equipment for feasibility study.

Research questions: We strive to answer following questions. Can a pulsed or CW radar waveform be modified such that communications data can be embedded? If so, how? What are the effects to the radar in terms of detection performance? Finally, what kind of SER is possible for the communications waveform?

Findings: In our feasibility study, we were able to model the embedding of QPSK (Meager et al., 2016) into pulsed waveform, and we were able to model the embedding of that communications in LFM waveform (Liu et al., 2020). We were also able to design an MLE-MLD demodulator for both embedded waveforms. Additionally, we were able to design a machine learning DNN modulator for the QPSK communications signal. Three versions of DNN detectors were proposed each with varying SER performance. It was found that SER of the embedded communications could be a function of radar-to-communications ratio (RCR) and symbol-rate-to-bandwidth ratio (SRBR). We reported SER for both MLE-MLD and DNN detectors. The SER results were very promising and approached the ideal SER in some cases. Some experiments were performed confirming SER theoretical calculations. Both receiver detectors were robust.

Conclusion: In this work, we performed feasibility study of teaching (i.e., configuring) of existing radar systems to function as communications systems. We were able to model the embedding of low-power QPSK modulation into pulsed waveform and LFM waveform. Two receiver demodulators were proposed: MLE-MLD and machine learning DNN. Both techniques were successful in that they produced reasonable SERs. The radar detection probability was minimally affected.

Recommendations for Further Research

In this feasibility study of "teaching radars to communicate," it was proposed that low-communications waveform be injected into radar waveforms such that communications to a receiver were feasible. To that end, we also proposed two types of receiver detectors, a maximum-likelihood estimator coupled with maximum likelihood detection (MLE-MLD) and a machine learning deep neural network (DNN). Investigation into their symbol error rate (SER) performance showed that receivers were feasible. While the receivers were proposed, it is not clear, however, how the transmit waveform may be implemented in existing radar systems in terms of hardware. It is recommended that for a particular system of interest, an investigation into programming the waveform into its transmitter digital module or component such as field programmable gate array (FPGA) should be performed. If this is not feasible, it is then recommended to pursue further research into designing a transmitter attachment capable of synchronizing with the radar.

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NPS-20-N063-A: MEMS Acoustic Sensor for UAV Detection and Localization

Researchers: Dr. Fabio Durante Pereira Alves and Dr. Gamani Karunasiri
Student Participation: LCDR Jaemin Yang FORNATL KOR

Project Summary

The proposed one-year research effort continued exploring the feasibility of using microelectromechanical systems (MEMS) acoustic sensors to detect and localize unmanned aerial vehicles (UAVs). The detection and localization scheme is based on the hearing organ of the parasitic fly *Ormia ochracea*, which performs a signature-based detection of chirping crickets. To do that, we studied and analyzed the ability of two Ormia-based MEMS sensors to provide the direction of arrival of small multi-rotor UAVs. Two collocated canted sensors were assembled in an anechoic chamber and used to measure the direction of arrival of a 45 cm Hexacopter. Preliminary results indicate a great potential for this type of sensor to be used as an aid for counter UAV operations.

Keywords: *microelectromechanical systems sensors, MEMS sensors, unmanned aerial vehicle, UAV, acoustic signature, sound detection directional acoustic sensors*

Background

Currently, small unmanned aerial vehicles (UAV) are used in many fields, including shipping, delivery, architecture for creating topographic surveys, photography, search and rescue, security and defense among many others. The technology has enabled a tremendous reduction in cost; therefore, the number of small UAVs is expected to continue rising as their applications are expanding. In the same way that small, multi-rotor UAVs can be explored as great assets in the defense realm, they also pose a considerable threat to military operations. Many efforts have been conducted to prevent UAVs from performing surveillance, terrorist, or military attacks. Potential countermeasures cannot be employed, however, if the threat is not detected.

Recent studies have sought to develop small UAV-detection systems using radar, electro-optics (i.e., cameras and infrared [IR]), acoustics, and radio frequency (Birch, Griffin & Erdman, 2015). Each method has its own specific limitations; one that is common to all, however, is the difficulty of detecting smaller targets. An approach that is independent of the size of the aircrafts is acoustic detection that targets the sound emitted by the aircraft's rotors. Furthermore, acoustic detection is a passive process, which can be important in defense applications. Although many acoustic systems have been proposed for detection of small UAVs, the proposed systems share at least one common characteristic, the use of conventional microphones, which suffers from detection range limitations and requires complex array arrangements for localization of the source. Researchers from the Sensor Research Laboratory have been investigating an approach to detect the presence and the direction of small UAVs using microelectromechanical systems (MEMS) directional acoustic sensors, based on the anatomical structure of the ears of the parasitic fly *Ormia ochracea* (Miles, Robert & Hoy, 1995). These sensors have proved to be very efficient in providing unambiguous directional detection of single-tone acoustic sources and blast sounds such as bomb explosions and gunshots (Mutton, 2019). Building on this success, the objective of this study was to demonstrate the ability to detect the bearing of a small UAV using colocated, canted, Ormia-based MEMS sensors. These sensors have the advantage of possessing directional accuracy (Mutton, 2019), a very small form factor, and low power consumption¾even with the inclusion of the amplification electronics.

Findings and Conclusions

To prove the concept just described, this study relied on the similarities between acoustic signatures of small multi-rotor UAVs (Feight et al., 2017; Zhou et al., 2019), and concentrates on the general characteristics of the sound generated by a particular small hexacopter (Yuneek Typhoon) in hovering regime. Based on these characteristics, an Ormia-based MEMS acoustic directional sensor was designed to exhibit resonant response around 700 Hz, to match the strong emission of the source. One advantage of operating at resonance while having a reasonable quality factor is the ability to naturally filter out a large portion of undesirable background noise.

Several MEMS sensors were characterized, and a pair with matching frequency response was selected and mounted with a canted angle of 15 degrees. The sound of the Typhoon was played in an anechoic chamber while the sensor was rotated. The data from both sensors was recorded, averaged over time, and a simple algorithm based on the difference over sum was used to compute the direction of arrival. Several average or integration time intervals were used for comparison purposes. The results show reasonable agreement between the actual and measured angle of arrival with average error around 11 degrees. No signal conditioning such as filtering, rectification, smoothing, etc., or signal processing other than integration was applied. It is observable that no ambiguity exists in the range of detection, and with the application of simple calibration methods such as fitting curves or lookup tables, accuracy can greatly increase.

This result is significant since such detection has never been obtained before with colocated sensors having a total footprint of about 5 cm. This proof-of-concept, performed with the Yuneek Typhoon, represents only the first step in direction of arrival (DoA) determination of small multi-rotor UAVs by acoustic detection, without the need of sensor arrays or distributed sensors.

Some observations made during this study are worth highlighting. First, although this study was conducted using a particular small multi-rotor UAV, it can be inferred from the open literature data that the acoustic spectral characteristics of similar small multi-rotor aircraft are comparable. This allows for the studied sensor configuration to be used indiscriminately for a large number of small multi-rotor UAVs. Second, the canted configuration used in this study imposed an offset angle of 15 degrees between normal incidence and the sensors' azimuth. This limited the range of detection between –75 and 75 degrees. Smaller offset angles could be used to expand this range. Furthermore, the introduction of a third sensor could provide 360 degrees of coverage. Third, the MEMS sensors can be designed to exhibit multiple resonances (controlled spectral sensitivity) according to the acoustic signature of the multi-rotor aircraft. This would enhance the sensitivity while preserving the natural filtering of undesired frequency bands. Furthermore, by exploring the differences in signatures, it is possible to perform identification. Fourth, comparable results were obtained for integration times between 0.5- and 10-seconds. Therefore, fast detection can be employed, which could be particularly interesting for tracking.

Recommendations for Further Research

An assembly with colocated canted Ormia-based MEMS sensors was used to determine the direction of arrival (DoA) of the sound produced by a small multi-rotor unmanned aerial vehicle (UAV). Preliminary results show an average azimuthal error around 11 degrees, indicating the great potential for DoA determination without the need for complex sensor arrays or distributed sensors.

It is important to highlight that the results obtained by this study are limited to controlled conditions and need to be expanded to field tests and realistic environment background. The future work should not only encompass the appropriate application of signal processing and correction algorithms but also extensive experimentation in open field. A network of distributed sensors should be tested for 3-D localization and tracking of small multi-rotor UAVs and potentially other acoustic sources of interest. New demodulation techniques must be investigated to improve performance as well as sensor ruggedizing for field operation.

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NPS-20-N064-A: Implosive Seabed Effector Performance

Researcher: Mr. Jarema Didoszak
Student Participation: No students participated in this research project.

Project Summary
Seabed effectors are devices designed to deal with adversarial threats along the ocean floor. These tools must not only be effective in performing their own mission but must also be resilient enough to withstand the devastating effects of static pressure at deep ocean depths, the concussive pressure waves generated through underwater explosion and implosion events and other factors associated with operating in such an inhospitable environment. Investigation of pressure-loading effects resulting from the rapid collapse of air cavities was performed via analyses of various finite element models. Trends of prior research were interpreted and used to inform the current study. Using basic models, the sensitivity of the structural response and corresponding efficacy of pressure loading in creating material or functional failure in the targets was examined. Design factors such as material, shell thickness and environmental parameters were varied to exercise the problem set. Results indicated that source shape, size and radial standoff distance drive omnidirectional response in thin-walled structures constructed of traditional materials, though further study is required to characterize unidirectional loading interactions and response of other materials having higher strength to density ratios such as composites.

Keywords: *underwater explosion, implodable volume, seabed target, seabed effector, fluid structure interaction*

Background
Seabed warfare includes locating, identifying, marking, and neutralizing undesirable seabed targets. These targets come in many sizes and shapes, consisting of various structural materials and designs. Furthermore, they may be located floating just above the bottom, semi-submerged, or resting on the ocean floor. Key issues in understanding the practical use of implosion as a viable tool for seabed warfare are: 1) matching effectiveness of the seabed effectors against the selected target characteristics, and 2) ensuring the safety of the delivery vehicle/device itself.

Traditionally, underwater explosions (UNDEX), which are typically characterized by the rapid release of energy from detonation of a high explosive, resulting in a shock pressure wave front, have been used to defeat subsea threats. However, these high-yield devices also come with high risk. Implosion results in a radiating pressure pulse caused by the sudden energy release of a failed pressure vessel, void, or air cavity of other implodable volumes under the water. This violent event is another option by which to impart the lethal force capable of damaging or failing an underwater target, vehicle, or structure. While the phenomena associated with UNDEX has been studied more extensively, implosion phenomena and effects are less well known.

Initial work in the study of implosion was completed by Rayleigh (1917). Further experimental study to better understand “bubble dynamics” was performed by Gilmore (1952). Structural response of implodable volumes was studied by Isaacs and Maxwell (1952) and supplemented work in characterizing underwater sources was performed by Urick (1963). Vanzant et al. (1967) documented near-field undersea implosion effects using aluminum spheres. Past researchers have reported that conveying trends based on experimental pressure measurements, such as the increase of implosion-generated hydrodynamic pressure with corresponding increase in size and collapse pressure, are representative of this behavior, yet have found predictions to more challenging due to the variability in the data. Thus, the use of buckling theory of thin shell structures, Timoshenko and Gere (1961), and finite element method solvers employing fully coupled fluid structure interaction techniques such as the Dynamic System Mechanics Advanced Simulation (DYSMAS) hydrocode by Wardlaw et al. (2003) has dominated most recent research in this area.

Much of the work concerning this topic has been carried out by the Naval Surface Warfare Centers, Naval Undersea Warfare Centers, and associated collaborators. More recently Krueger (2006), Turner (2007), Tacey (2007) as well as Chamberline (2013) reported on implosion energy release and effects using modeling and simulation, small, scaled experiments, and testing. Researchers also confirmed good correlation with the finite element modeling approach using physical testing, Turner (2013) and analytical and numerical analysis, Sugimoto (2020). Thus, physics-based modeling of implosion events as a means of better understanding the damage potential for neutralization of undesirable targets via seabed effector, or threat defeat device, is reasonable and demands further study.

Findings and Conclusions

The approach utilized in this study is as follows. The design space representing the deep ocean environment was established based on typical operational values. Next the seabed effector was modeled using information provided by the sponsor and from review of previous studies. A representative target was chosen and modeled, and the fully coupled structural hydrocode was used. Simulation results were analyzed for failure trends in the target based on source volume, configuration, and radial standoff distance. Comparisons were also made with general analytic predictions.

Energy release is a function of depth, displaced volume, implodable geometry and material. Implodable volumes producing yield like typical high explosive charges were investigated against representative deep-ocean targets. Compared to explosive charges, the implosive sources were considerably larger in size and much more massive. From prior studies, it was observed that for the equivalent diameter between a spherical and a cylindrical void, the globe produced a higher maximum pressure, while the sphere's pressure decayed more rapidly than that of the cylinder. This demonstrated that the cylinder would provide higher pressures at greater standoff distances than the spherical source; however, for purposes of this study, near-contact to near-field radial distances were of interest and as such primarily spherical volumes were considered in this study. Thus, the nominal seabed effector was modeled as a one meter thin-shelled sphere consisting of aluminum alloy, with other diameters and materials examined for comparison.

A simulated pressure pulse in deep water was generated by structural failure resulting from intentional compromise of the spherical shell using the DYSMAS program. In each case, the volume imploded due to an exterior hydraulic pressure in excess of the yield strength. This was modeled via a failure defect used to induce collapse of the source upon initiation of the simulation. The surrounding water volume was treated with radiating boundaries such that wave front reflections were minimized at the edges of the multi-degree computational domain. A simple shaped steel target structure was modeled as being near to, but not in contact with, the sea bottom, and near the source.

Results showed that the implodable volume source generated a similarly shaped initial peak as compared to underwater explosion events, yet with little bubble pulse reloading as would be expected in the latter case. As expected, induced damage upon the target increased with proximity of the source and as a function of source geometry. Attempts at directional energy release using the spherical shell model produced inconsistent results.

Regarding delivery vehicle survivability, where additional material weight and space limit up-armoring, inclusion of a double-wall structure with an air gap reduced the peak pressure experienced by the structure. Another alternate method previously suggested, though not investigated here would be the use of deformable interior structure as a means of dissipating the shock wave loading; however, incorporation into the design of the seabed effector may prove to be challenging.

Recommendations for Further Research

Influence of the slender ratio on peak pressure is well known in near-field, underwater explosion testing. Additional research is recommended in the directional focusing of implosion-initiated shock fronts for determination of potential in generating increased pressure loading on representative targets operating in the deep-sea environment from additional source geometries. The concept of implosion induced water-jetting as a means of furthering the damage mechanism for seabed effectors is also recommended for further study. Finally, detailed investigation of the influence of ocean bottom proximity, shape and composition, as previously studied by Walters (2013) for UNDEX related problems, would provide further insight regarding damage potential of similarly positioned implosion cases.

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NPS-20-N071-A: IPCL Gap Analysis and Visualization

Researchers: Dr. Magdi Kamel and Dr. Shelley Gallup
Student Participation: No students participated in this research project.

Project Summary

The Warfare Improvement Program (WIP) process is the formal framework for capturing, vetting, and prioritizing Fleet capability needs to improve readiness and optimize resources for Navy forces in the execution of Combatant Commander (CCDR) tasking. For each mission area, a WIP Fleet Collaborative Team (FCT) is constituted to participate in events that inform development of annual output products. A ranking tool is utilized throughout the WIP cycle to aid in objective prioritization of capability gaps and generation of an Integrated Prioritized Capabilities List (IPCL) (Commander U.S. Pacific Fleet, 2013). In this research effort, we developed a methodology based on Multi-Criteria Decision Analysis (MCDA) methods to calculate and visualize a capability gap score at any given point in time. This methodology depicts capability gap resolution progress based on substantiated real-time information in order to 1) support prioritization of capabilities based on hard data, 2) provide a clear and concise picture of progress being made, or not made, to close identified gaps and/or provide a capability, and 3) support the creation of a central repository for organizations to distribute pertinent information.

Keywords: *data visualization, gap analysis, risk assessment*

Background

Commander, Naval Surface and Mine Warfighting Development Center (SMWDC) is tasked to provide oversight, alignment, synchronization and end-to-end assessment of WIP for mission areas under the cognizance of the Surface Type Commander. The WIP process is the formal framework for capturing, vetting, and prioritizing Fleet capability needs to improve readiness and optimize resources for Navy forces in the execution of CCDR tasking. For each mission area, SMWDC HQ is responsible to ensure a WIP FCT is constituted to participate in events that inform development of annual output products. Each WIP conducts Executive Working Groups (EWG) in QI and Q2 and a symposium in early Q3 of the current Fiscal Year Program Objective Memorandum (POM) cycle. A SMWDC HQ N8/9 endorsed ranking tool is utilized throughout the WIP cycle to aid in objective prioritization of capability gaps. Annual Capability Area Assessment (CAA) is a collaborative effort led by the EWG Chair with the support from the FCT working group leads and the Warfare Development Center. Q1 and Q2 intel briefs and FCT updates received during EWG help inform creation of the CAA and ultimately provide the "homework" or supporting documentation for prioritization of capability gaps. Each Capability Area Owner (CAO) then briefs their CAA and IPCL to SMWDC N00. The CAA report serves as the basis for the development of the current WIP cycle IPCL through the efforts put forth in the WIP Symposium (Commander, Naval Surface and Mine Warfighting Development Center, 2018).

Findings and Conclusions

There are myriad sources of information and knowledge that identify warfighting capability gaps or provide recommendations to close gaps, and therefore, improved capabilities to the fleet. What appears to be missing is a comprehensive system, and responsible entity, which captures all that information in one place to provide a clear and concise picture to measure progress being made to close identified gaps and/or provide capability. This research addresses this shortcoming by developing a methodology for calculating and visualizing capability gaps at any given point in time, with the goal of providing Navy leadership with a clear picture of what has been accomplished, what remains to be done, and what is the critical path needed to close the gap and deliver a capability.

Our work resulted in a proposed methodology for calculating and visualizing capability gaps, based on Multi-Criteria Decision Analysis Methods (MCDA) and consists of the following steps (Parlos, 2000): 1) Identifying factors that influence a capability gap using an appropriate capability framework, 2) Rating capabilities on identified factors, 3) Assigning weights to identified factors, 4) Calculating a capability gap score from ratings and weights using an appropriate MCDA model, 5) Conducting a sensitivity analysis to evaluate how other ratings and weights affect the capability gap score, and 6) Visualizing capability gap scores across time and factors using a dashboard. The capability framework used in this research effort is the Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLP), a framework designed to provide design solutions tailored to meeting warfighting requirements.

Recommendations for Further Research

For future research, we recommend revisiting the capability management framework used in this effort i.e., Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) by adding new and/or removing existing factors. These factors can be subsequently grouped into a hierarchy of high-level factors and low-level sub-factors. We also propose investigating different approaches to weighting the factors, which determine a capability gap as well as the methods for combining capability factor scores into an overall capability gap score. Most importantly, we recommend applying the proposed methodology to two or three real-life scenarios of desired capability and visualize the resulting gap scores across time and influencing factors. Finally, we recommend refining the proposed dashboard by incorporating additional charts and graphs to better visualize the capability gap scores.

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NPS-20-N072-A: 5G Cellular Communications for Flight Deck Radios to Reduce Electromagnetic Signature

Researcher: Dr. Valdis Berzins

Student Participation: LT Sabrina Atchley USN, LCDR Brandon Beckler USN, Maj Marc Bucks USMC, LT Javen Davis USN, MAJ Erik Dubois USA, Capt Sean Gilroy USMC, LT Allen Golphin USN, Capt Steven Gore USMC, Maj Ousmane Goumandakoye USMC, Capt Matthew Gurrister USMC, LCDR Bryan Kauffman USN, LT David Nygren USN, LCDR Boswyck Offord USN, LT Kenneth Pittner USN, Capt Max Schlessel USMC, Capt Ryan Sohm USMC, LT Benjamin Travers USN, LT Alexander Washofsky USN, Capt Shane Wescott USMC, and Capt Daphne Williams USMC

Project Summary

We investigated how the Navy can take advantage of fifth generation wireless systems (5G) mobile communications advancements and whether flight deck personnel can use that technology to their advantage. 5G radios use higher frequencies that can support high data rates and narrow beams but have limited communications range. The limited range can be an asset in the context of flight deck communications because the Navy's flight deck radio is a unique signal that could compromise the location of an aircraft carrier (CVN) when conducting flight operations if adversaries receive it. Researchers and students developed and analyzed requirements models for flight deck communications and conducted studies on potential benefits and disadvantages of using 5G radios in that context. The study found that 5G radios should be beneficial for flight deck operations and recommends that the theoretical estimates developed in the study be validated by measurements in realistic operating environments.

Keywords: *5G, CVN, flight deck radios, reduce electromagnetic signature, requirements*

Background

Electrometric propagation is a function of energy in the signal and frequency of the signal. Higher frequency signals lose their energy in shorter distances. To compensate for this attenuation, the 5G radio uses a directional phased array antenna to direct the energy to the receiver. The directional antenna system significantly complicates the detections process for adversary EM sensing systems, because the signal is very weak in directions other than that of the main beam. Other potential advantages of using 5G radios include small size for antennas and low cost for the radios, especially if the commercial market for

5G equipment continues to expand.

Findings and Conclusions

The purpose of the study was to evaluate the benefits and possible disadvantages of future use of 5G radios to support flight deck operations on Navy ships. The study examined the extent to which 5G radios could reduce the electromagnetic footprint of CVNs and other ships that conduct flight operations and examined some new capabilities that could be supported by 5G radios but not by the legacy approach. Reducing the electromagnetic signatures of the ships would contribute directly to reducing the risk of attack by adversary platforms such as submarines should an active conflict occur.

The study analyzed the proposed system using data from the open-source literature and from Navy subject matter experts. Models of various aspects of the system were then constructed and analyzed to determine comparative benefits and disadvantages of the two systems for flight deck communication.

The study found that high frequency 5G signals are attenuated significantly faster by the atmosphere than the signals used in legacy flight deck radios, and that application of the technology should provide a reduction in electromagnetic signature. The results include a quantitative characterization of the amount of reduction in external signal strength to be expected, and recommendations on how to choose operating frequency, antenna placement, and beam forming techniques to minimize the electromagnetic signature.

5G radios use digital signals, which are amenable to digital signal processing and could support services such as error correction and encryption. Legacy flight deck radios use analog signals and do not provide services other than plain voice communication. We found that several benefits of the 5G system would be best realized via integration with other ship systems. For example, extending the reach of the flight deck communications to include the pilots of the aircraft on deck should improve safety and streamline operations.

The study found that the disadvantages of using 5G radios include possible health hazards and recommended some low-cost mitigations that should reduce exposure to such hazards.

Recommendations for Further Research

Initial results of the study are promising. Recommend physical studies to measure 5G signal attenuation in actual shipboard environments to validate the results of the study, which were based on commercial data and theoretical modeling of signal properties. Complementary studies should determine signal levels that are detectable by potential adversaries and detection ranges that are of concern. If the results substantiate effectiveness in reducing electromagnetic signature, recommend further studies to optimize configuration and placement of 5G antennas for platforms that conduct flight operations, and to develop adaptive signal control algorithms that can continuously adjust signal strength to the minimum necessary for reliable communication relative to current weather conditions. The study also recommends further research on potential health effects of 5G radio use, because there is currently very little reliable data on this.

NPS-20-N076-A: Structural Analysis of 3D Printed Polymeric Materials and Associated Orientation-Dependent Mechanical Properties

Researchers: Dr. Andy Nieto, Dr. Young Kwon, and Dr. Donald Brutzman
Student Participation: LT Michael Pizzari USN and LT Charles Hodgkins USN

Project Summary

The advent of 3D printing has brought forth exciting possibilities for manufacturing and repair at the point of need. The Navy has interest in using 3D printers on board the fleet to manufacture parts that are difficult to obtain or as temporary replacements. This research aims to expand the potential uses of 3D printed parts beyond "good enough" or as temporary replacements into fully functional load-bearing components. As such, a deeper understanding of the effect of 3D printing parameters on mechanical properties is requisite. A systematic understanding of rastering patterns, layer thickness, and build direction on mechanical properties is investigated in this study. Two polymeric materials widely used in 3D printing, polylactic acid (PLA) and polyethylene terephthalate (PET), are used in the current study. Tensile behavior of these specimens is quantified using standardized testing. In addition, composites utilizing PLA as a base material plus an additional bronze or steel particulate reinforcement are tested in compression. Layer thickness was varied from 0.1 mm to 0.2 mm. Rastering patterns were varied from parallel lines, alternating 90 shifted layers, and concentric. Standardized specimens were printed either in the XY plane or in a "vertical" Z direction to understand influence of build direction. The results show that 0.1 mm layer thickness consistently results in enhanced mechanical properties, including strength and toughness. Aligning the fused filaments with the loading direction is shown to yield significant increases in ductility and toughness. Linear and crisscross patterns typically yield lower inter-filament porosity and result in greater mechanical properties. As a result, this newly attained understanding of printing parameters and their effect on structural performance will enable 3D printed parts to be used not merely as temporary "good enough" replacements, but also as fully functional components.

Keywords: *3D printing, mechanical properties, orientation effects, polymer matrix composites*

Background

This project is motivated by the desire to transition 3D printed materials from "good enough" or emergency-use parts to reliable, structural, load-bearing parts and components. This task is complicated by the flexibility of 3D printing that yields myriad parameters for printing a given structure. A few studies have begun to elucidate the role of printing orientation and defects on the resulting mechanical properties of 3D printed materials. Understanding the effect of printing direction and parameters such as layer thickness and rastering pattern could optimize the properties of 3D printed polymers and make them comparable to polymeric parts formed by convention processes. Another promising development has been the recent production of composite filaments suitable for 3D printers. Use of a secondary metallic phase could further provide the 3D printed material with the necessary strength to be used for structural load-bearing applications. This study has investigated the effects of layer thickness, rastering patterns, and build directions on the mechanical properties of 3D printed PLA, PET, and bronze reinforced PLA composite.

Findings and Conclusions

The investigations partaken in this study stem from interest from the Commander of Submarine Forces of the US Pacific Fleet (COMSUBPAC) in utilizing 3D printers in the submarine fleet. The need of COMBSUBPAC is twofold: 1) given the myriad printing parameters possible, some down selection is needed to guide Sailors or other end users, and 2) given the potential for manufacturing at the point of need, it is critical to determine the suitability for using 3D printer polymers as load-bearing structural components. This study is an important step in understanding the parameter space and mechanical performance of 3D printed polymers that will enable their integration in submarine fleet applications. This could allow Sailors to print replacement components or even design and produce new parts needed on demand within their challenging operational space.

A literature review was conducted to determine the current understanding on the mechanics and mechanical behavior of 3D printed polymers and to survey which parameters have already been systematically studied. Layer thickness, rastering patterns, and build directions have received little attention in the research community. These parameters are typically determined from a manufacturer's default setting or recommendations, which may oftentimes be tailored toward quick demonstrations rather than optimized mechanical behavior. Systematic studies are carried where only one parameter (layer thickness, rastering pattern, or build direction) are varied at a time. In addition, it is known in the polymer literature that the addition of metallic or ceramic particles can enhance mechanical properties. As such, exploratory studies are carried out on recently developed metal infused polymer filaments for 3D printing.

Findings confirm that 3D printed polymers largely behave like conventional fiber-reinforced composites. As such, thinner layers yield greater strength and toughness, and properties are enhanced when the printed filaments (analogous to fiber reinforcements) are aligned with the loading direction. A linear rastering pattern enables all the filaments to be aligned in the loading direction and, as such, this rastering pattern typically yielded the high mechanical properties. Utilizing rastering patterns and build directions that don't align filaments with the loading direction can dramatically change deformation characteristics from ductile (high toughness) to brittle (low toughness).

These findings provide general and specific guidelines for printing components onboard submarine and across Navy applications at large. Filaments should be aligned in the loading direction and, if time is not a significant constraint, thin layers should be used to obtain the highest mechanical properties and ensure high structural integrity of the printed parts or components. In the long term, composite approaches used in conventionally processed ceramics should be further explored for 3D printing applications. This includes further characterization of existing commercial composite filaments, as well as the development of new advanced composite filaments tailored for specific Navy applications.

Recommendations for Further Research

The research has shown the importance of understanding the mechanics of 3D printed polymeric materials and how processing parameters control those mechanics. It was shown that the very nature of the mechanical response, from brittle to ductile, could be modified by changing the rastering pattern or build direction. The use of finer print layers also imparts greater strength and ductility across all specimens tested, either pure PLA, pure PET, or bronze reinforced PLA composites. The print time is longer when using finer layers, but it is warranted if the components printed are intended for structural load-bearing applications. If the load direction in the given component or part is known, the printed filaments should be aligned in that direction, as higher strength and toughness were consistently seen when filaments were deposited along the load axis. These findings are consistent with conventional composites, whose structure is mimicked by the layer-by-layer deposition process used in fused deposition modeling 3D printing. Additional studies are planned on polycarbonate to further confirm the generalization of these observation across different types of polymers. Monolithic polymers will undergo compression testing to compare with the composites' specimens, and likewise tensile testing will be performed on PLA-bronze and PLA-steel composites for comparison with pure PLA. Early results show great promise for the composite filaments in attained high strength and toughness, properties critical to structural load-bearing applications. Further studies on fatigue and wear are recommended to better simulate loadings incurred in the environment. The promise of the composites tested here point towards an increased need to develop advanced composite filaments with tailored properties for loading types of environments.

NPS-20-N233-A: Augmented Reality Use During Aircraft Moves Decrease Aviation Ground Mishaps

Researchers: Mr. Perry McDowell, Dr. Meghan Kennedy Cortez, and Ms. Rabia Khan
Student Participation: Capt Colton Fetterolf USMC

Project Summary

According to FY2014–FY2019 United States Navy (USN) Web-Enabled Safety System data, 35 mishaps and 24 hazardous incidents occurred because of aircraft towing collisions, resulting in a monetary impact of over $14.4 million. This project explored the concept of using augmented reality (AR) as an operational tool to aid the person overseeing the towing process, who is referred to as the "tow crew director" (TD). The study also examined the extent to which AR enhances the TD's situational awareness.

Feasibility testing of an AR system was conducted by creating a virtual reality (VR) program called Aircraft Towing Enhanced with AR (ATEAR). ATEAR was designed to boost a TD's understanding of an aircraft's edges relative to surrounding objects on a flight line during the towing process. The research objective was to compare human performance between a standard view and an AR view. Twenty scenarios were developed to simulate execution of one towing event. Hit, danger, caution, and miss scenarios were created for each environment.

Due to COVID restrictions, qualified aircraft maintenance personnel could not be test subjects. However, initial testing results of Naval Postgraduate School students indicated that an AR system has the potential to increase a tow crew director's situational awareness and, in turn, decrease the likelihood of future towing incidents. The AR system- enabled subjects to identify potential collisions earlier than their standard-view counterparts. Additionally, survey results indicated that subjects believed this system could have a positive impact on a TD's ability to effectively control the towing evolution of an aircraft in an efficient and safe manner.

After the completion of several minor changes, ATEAR could be further tested in an official experiment. Data collected from an official experiment utilizing aircraft maintenance personnel with the requisite skill set would provide further justification for future development of such an AR system.

Keywords: *naval aviation, mishap, aircraft collision, Marine Corps aviation, towing, augmented reality, AR, virtual reality, VR, Aircraft Towing Enhanced with AR, ATEAR*

Background

Since 2014, naval aviation has experienced a rise in aircraft ground mishaps (AGMs). From FY2014-FY2019, the USN and United States Marine Corps (USMC) experienced 35 mishaps and 24 hazardous incidents because of aircraft towing collisions. Each incident was unintentional and completely avoidable, yet these incidents cost the USN and USMC $14.4 million over the 5-year period. These evolutions are performed by maintenance personnel who are commonly referred to as "maintainers" in naval aviation.

Due to the ramifications of AGMs across the fleet, both the USN and the USMC solicited assistance from consulting agencies to conduct independent readiness reviews of mishap data, current practices and procedures (Nguyen, 2018; Glueck, 2017). The aircraft with the highest mishap rate in the USN was the F/A-18. Consequently, the USN requested the Center for Naval Analyses to analyze AGMs in the F/A-18 community (Nguyen, 2018). The USMC requested Booz Allen Hamilton conduct an all-inclusive analysis of AGMs on all types of aircraft (Glueck, 2017). The general consensus from both studies was that the rise in AGMs could be attributed to inexperienced maintainers (Nguyen, 2018; Glueck, 2017). To date, no studies have focused specifically on towing incidents (Fetterolf, 2020).

As such, this project aimed to view the problem from a different angle. A probable cause for towing mishaps is the lack of visibility of flight control surfaces during operations. The standard paint scheme of all USN aircraft is a mixture of light and dark gray, which is difficult to see in both dark environments and extremely bright environments. The color of concrete also causes segments of the aircraft to blend in with the ground. Outfitting at least one member of an aircraft tow crew with an AR system that provides additional information about the aircraft position relative to objects around it may be an effective way of increasing situational awareness to the tow crew, consequently reducing the number of AGMs (Fetterolf, 2020).

The following hypotheses were established:

Hypothesis 1
There is a difference in collision detection rate between the standard view and AR view, $dps - pAR \neq 0$.

Hypothesis 2
There is a difference in mean stopping distance between the standard view and AR view, $\mu d \neq 0$.

Hypothesis 3
There is a difference in confidence levels between the standard view and AR view, $\mu d \neq 0$.

Research suggests that it is possible to use VR as a platform to design and test various AR systems without incurring unnecessary costs (Geoghegan, 2015). VR provides a controlled environment to test the AR system and enables the ability to run numerous tests to determine the effectiveness of an AR system prior to physically producing a real product. This virtual environment also provides a method of creating an AR system that meets the demands of the maintainers who would utilize the device directly. Running scenarios in a VR environment prevents putting the safety of real aircraft and maintainers at risk when trying to test the feasibility of an AR system, and it also facilitates the capture of useful metrics.

Findings and Conclusions

The Commander, Naval Air Forces (CNAF) staff posed the initial research question of, can AR aid in towing aircraft? Simulating towing an aircraft in VR provided a risk-free method and an objective means of measuring human performance. We immersed each test subject in ATEAR using the Oculus Rift head-mounted display (HMD) and measured their performance. The design of experiment included: surveys, an ATEAR training session, and the main experiment scenarios.

Scenarios were categorized as:

Hit: the aircraft would collide with an object if not stopped.
Danger: the aircraft passed close enough to warrant a whistle.
Caution: the aircraft passed within three feet of object.
Miss: the aircraft never passed within three feet from an object.

The limited sample size from initial testing (n=8) prevented us from formally testing each hypothesis. However, descriptive statistics provided some insight.

We examined hypothesis 1 as follows:

In "Hit" scenarios, collisions were properly predicted 74 percent of the time in AR versus 53 percent of the time using the standard view. However, in "Danger" or "Caution" scenarios, the AR system (63.16%) proved to be less accurate predicting collisions than the standard view (84.21%). This might appear to be a negative implication of using the AR system, but this means that 36.84% of the time in AR subjects chose to blow the whistle because they felt that a collision was going to occur, which is a desirable action during real world towing events.

We examined hypothesis 2 as follows:

On average, subjects stopped the aircraft further away from the scheduled collision point using the AR view than the standard view. Thus, the AR system nearly doubled a subject's ability to determine a collision was going to happen and stop the towing evolution.

We examined hypothesis 3 as follows:

We asked subjects questions to gauge their confidence in their decision to either stop the evolution or allow it to continue. For "Hit" scenarios where the subject stopped the evolution, there were negligible differences in confidence between the two conditions. For "Danger" scenarios where the subject stopped the evolution, those using the ATEAR showed less confidence. We also note that those with the standard view were more confident, albeit incorrectly, that a collision would occur. For both "Hit" and "Danger" scenarios where the subject did not stop the evolution, those using ATEAR were more confident than those using the standard view. There was no substantial difference in speed modulation between AR and standard views for both "Hit" and "Danger" scenarios.

Despite use of the AR view leading to a lower degree of confidence for "Hit" scenarios, seven of the eight subjects felt that the AR view helped their understanding of the aircraft's location in relation to other items in the scene. The results showed that the subjects had confidence in the system and felt it was easy to use. All subjects felt that a similar AR system should be incorporated in the towing process across the fleet.

Recommendations for Further Research

The results from our initial testing showed that an augmented reality (AR) system may increase the situational awareness for tow crew directors. However, an official experiment with the proper personnel would be necessary to further justify the development and implementation of an AR system in the aircraft towing process. Our initial testing participants were not representative of the personnel who would use the AR system in the fleet. We recommend that a formal experiment be conducted using maintenance personnel after Aircraft Towing Enhanced with Augmented Reality (ATEAR) is updated with the following changes:

In the AR tutorial section of the experiment, the script used for the pilot testing stated, "If the wingtip indicator is red, DO NOT assume the aircraft will collide with the object." We believe the subjects' response to a red wing tip track from the AR system could have skewed the stopping distance data. Moving forward, we propose altering the script in a way that associates wing tip colors to distances. During the "hit" scenarios in which a whistle was blown, the scenario was paused while the subject completed a confidence question. Then, the scenario continued to run until the aircraft reached its scheduled stopping point. During this experiment, subjects could hit a "Proceed" button to go onto the next scenario. However, doing so prevented recording of certain data, so we recommend that button should be removed in future experiments.

Inconsistencies observed in the "Danger" and "Caution" scenarios need to be removed to ensure that the test for each subject remains consistent.

We propose the creation of an AR system that consists of three components: AR display, receiver, and sensor pucks, which can be mounted to an aircraft. The proposed system is a minimal, lightweight, and purpose-specific system. The AR display would be a single lens mounted to the tow director's helmet and the receiver could be designed in such a way that a tow crew director could retain the minimalist receiver in their maintenance coveralls. Each sensor would provide position and other sensory data to the AR receiver.

For the proposed system, the most plausible tracking system would be one that utilizes organic tracking from the AR head-mounted display (HMD), which requires at least two cameras to capture data from sensors placed on the aircraft.

The use of the AR device for towing operations would need to become a requirement to the towing processes outlined in the specific T/M/S IETMs database and the NAVAIR 17-1-537 (Department of

Navy, 2017). Test sets and support equipment are classified as aircraft maintenance material readiness list program assets. We propose the complete AR system (AR HMD, AR receiver, and sensor pucks) be stored in a hard-sided case and be classified as an "Aircraft Towing Kit." The number of towing kits issued to a squadron would be based on the aircraft allowances for those squadrons.

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NPS-20-N273-A: Officer of the Deck Proficiency Assessment Methodology and Techniques (Continuation)

Researchers: Dr. Jesse Cunha and Dr. Jennifer Heissel
Student Participation: LT Vincent Salazar USN

Project Summary

In response to several high-profile ship collisions in 2017, the Surface Warfare Officers Schools Command (SWSC) implemented a program to assess the proficiency of first-tour U.S. Naval Officers of the Deck (OODs). The program has three components: a simulator exercise assessed by a post-command officer, written exams of rules of the road and seamanship knowledge, and a self-reported survey of OOD's operational experience and background. In a continuation of our study of the first round of data collected in 2018 (Cunha and Dearth, 2019), SWSC asked us to analyze the statistical relationship between proficiency, knowledge, and experience from data collected in 2019. They also asked us to make recommendations for how future assessment data can be collected and analyzed in order to inform optimal training and watchstanding policies.

The 2019 data contains a random sample of 66 OODs who were assessed at the end of their first tour. The experience survey revealed large variation in OODs' operational experience, partly stemming from significant variation in the time spent underway. For example, while the median first-tour OOD had 200 hours of experience, OODs in the 5th and 95th percentiles of the distribution had 18 and 855 hours of experience, respectively. In addition, 10% of experience was gained in a simulator, and at the time of assessment, most OODs had no watchstanding experience in the past 90 days. Assessment scores had an almost identical distribution as scores from the 2018 data collection round and were normally distributed around “average” proficiency. Although knowledge is positively correlated with assessed proficiency, we found no correlation between experience and proficiency.

Ultimately, the small sample size precludes our ability to make precise recommendations about optimal training policies. However, the Surface Community has developed a plan to assess all OODs at multiple points during their careers starting in 2021 and the resulting data, if consistently collected and stored correctly, will facilitate data-driven policy decisions concerning training, proficiency remediation, and officer detailing.

Keywords: s*urface warfare, Officer of the Deck, OOD, proficiency, experience, simulator, training*

Background

Historically, the U.S. Navy has not systematically assessed and recorded mariners’ ship-handling proficiency or operational experience at the individual level. Absent such information, it is difficult for the Surface Community to gauge the proficiency of their OODs, to track their proficiency over time (both growth through the career and the potential atrophy of skills in-between deployments), and to understand the impact of changes to training and policy. Following several high-profile collisions in the summer of 2017, the Surface Community instituted a series of policies aimed to remedy these shortcomings.

We studied a policy which instituted an assessment program with three parts: a simulator exercise in which OODs are assessed by a post-command Commander or Captain, written exams on Rules-of-the-Road (RoR) and Navigation, Seamanship, and Ship-handling (NSS), and a self-reported survey of the OOD’s operational experience and background. In 2018, SWSC applied this assessment to a random sample of 164 OODs who were in the middle of their first tours of duty aboard ship. Between April of 2019 and January of 2020, SWSC used the same assessment program to evaluate a sample of 66 OODs at the end of their first tours when they arrived in Newport, R.I. for the Advanced Division Officers School (ADOC).

Several other policies were introduced after the ship collisions, with the intent of improving OODs ship handling proficiency, including: increasing formal OOD schoolhouse training from 11 to 20 weeks; increasing the length of OOD’s first tours; requiring Surface Warfare Officers (SWSC) to track underway and simulator experience in a Mariner Skills Logbook; mandating that OODs have uninterrupted periods for sleep between watches, which coincide with our natural circadian rhythms; and instituting 10 formal assessments of ship handling proficiency throughout an OODs career.

Ultimately, we would want to study the impact of these – and future – policies on OOD proficiency, but the current amount and type of data is not sufficient for such analyses. In fact, such analyses are precisely what were called for in a recent U.S. Government Accountability Office (GAO) report (GAO, 2019). The planned future assessment data, if performed consistently and stored correctly, should facilitate analyses that can inform optimal policies.

Findings and Conclusions

The self-reported survey collected demographic and career information (commissioning source, ship class, and home port; age, gender, and prior enlisted status; the number of months spent underway and in-port) and detailed information on officer’s overall and recent experience both in a simulator and underway as OOD, Junior Officer of the Deck (JOOD), and Conning Officer (CONN). One of the recommendations from our FY19 analysis, which SWSC implemented, was to collect more detailed information in this survey. Compared to the original survey instrument, the 2019 version collected more demographic data (age, gender, and time spent in-port/underway), collected experience data as continuous variables (e.g., the number of months or hours) as opposed to categorical bins, and asked OODs to record their overall experience as well as their experience in the past 90 days, the latter of which allows us to study how the recency of experience relates to proficiency.

During the scenario, assessors filled in a rubric containing over 70 assessment points which helped them assign grades in four areas (management of bridge team, leadership, performance under stress, decision making) and one overall assessment category. The areas were graded on a 5-point scale and the overall assessment was on a 7-point scale. The inclusion of subjective sub-categories and the use of 5- and 7-point scales were recommendations from our FY19 report and provide a finer picture of OOD ability. The written RoR and NSS assessments each contained 20 multiple choice questions and covered standard material an OOD is expected to understand; these tests were unchanged from the 2018 assessment process.

Within our first set of findings, which concern the self-reported survey data on OODs experience during their first tours, several results stand out. In general, we found large variation across individuals in their operational experience. For example, while the median first-tour OOD had 200 hours of experience (both on the bridge and in a simulator), OODs in the 5th and 95th percentiles of the distribution had 18 and 855 hours of experience, respectively. Similarly, there were a significant proportion of OODs who had not completed any special evolutions as OOD on their first tour. For example, the median OOD completed only one straits transit (the scenario tested in the simulator) and 36 percent of the sample had never completed a straits transit as OOD. Notably, in the 90 days prior to arriving at ADOC and taking the assessment, the majority of OODs had no operational experience – either underway or in a simulator. These findings can be partly explained by the finding that the majority of OODs spend over half of their first tour either in a shipyard or in-port. In addition, the lack of experience within the past 90 days is due largely to the timing of this assessment during a lengthy schooling pipeline in-between an officer's first and second Division Officer tours.

Summarizing the assessment data, we found that the distribution of proficiency was normally distributed (i.e., symmetric with tapering tails) around the average score, both for the sub-categories and the overall assessment. When we transformed the overall assessment categories to match the 3-category scale used in 2018, we found an almost identical distribution of proficiency as in 2018, with about two-thirds of the sample being "average" one-sixth of the sample being "unsatisfactory" and one-sixth being "excellent." Finally, the written exam scores showed that a large fraction of students were not proficient: 30 and 58 percent of the sample "failed" the RoR and NSS exams, respectively.

Next, we performed analyses of the statistical relationship between experience and proficiency. Our main analytical tool was a multivariate regression model, where the outcome (the dependent variable) is the performance of OODs on the various measures of proficiency and the explanatory variables (the independent variables) are the demographic and experience-related variables captured in the survey. A multivariate regression framework is crucial in this context, because the explanatory variables are likely to be highly correlated with one another—for example, prior-enlisted officers are generally older, or those in high-traffic home-ports will likely have more experience in dense traffic settings.

While we find that proficiency is positively correlated with knowledge (RoR and NSS exam scores, and assessment category scores), we do not find any significant relationship between proficiency and experience. This lack of significant correlation is due in part to the small sample size of the 2019 data (in contrast, the 2018 dataset with 164 observations showed a positive correlation between proficiency and experience), and possibly also points to the inaccuracy of this self-reported data.

Recommendations for Further Research

Recent changes to SWO training and assessments as codified in the Surface Warfare Officer Career Manual (COMNAVSURFOR, 2019) offer opportunities to use future assessment and experience data to inform policy. In particular, the manual (and instructions preceding it) institute: the establishment of 10 assessments throughout an OOD's career which will constitute a population-level, longitudinal database of ship-handling proficiency, and the requirement to track experience in the Mariner Skills Logbook which will contain a complete, validated record of OODs' operational experience throughout their careers.

However, for this data to be useful for analysis, several issues must be addressed. First, the experience survey should be continually assessed to ensure detailed data collection, while minimizing reporting errors that result from survey fatigue. In particular, we suggest removing some of the sub-categories regarding hours of experience and numbers of special evolutions completed. Second, experience data is a necessary component of any future research effort. While we can continue to collect data from surveys at the time of assessment, it may be easier and less subject to recall bias to create a system by which the Mariner Skills Logbook data is routinely entered into an electronic format. Until logbooks are made fully electronic, this function could be performed by having SWSC assessors "audit" the logbooks of officers undergoing OOD assessments and having the "auditor" enter the required experience data. We strongly recommend the creation of a data repository for all future assessments and experience surveys (or Mariners Skills Logbook data) which can track individuals and cohorts over time. Third, the assessment scenario will need to be updated regularly so that officers always see a novel scenario in each assessment. When it is, we must ensure that assessments are reflecting a consistent measure of "proficiency" across cohorts and across different career milestones. In addition, the assessment scenario should also be evaluated to ensure it is testing the correct set of skills. For example, would an easier, a harder, a more complex, or a simpler scenario better assess the proficiency of an OOD? Lastly, assessors must be trained to ensure consistency and comparability across the population. To that end, we suggest creating a detailed "Assessment Guide" which codifies how to assign OODs to various proficiency scores, which will be especially useful to prevent inconsistencies when assessment personnel rotate positions.

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NPS-20-N279-A: Assessment of USV Certification Requirements for COLREGS Compliance, Anti-Tamper, Environmental and General Safety

Researchers: Mr. Brian Wood, Dr. Shelley Gallup, Dr. Duane T. Davis, and Dr. Douglas J. MacKinnon, Capt Charles Good
Student Participation: LT Christopher Anderson USN and LT Michell Oberholtzer USN

Project Summary

The Navy's family of Unmanned Surface Vessels (USV) needs rational, robust and repeatable certification criteria for Collision Regulation (COLREGS) compliance, anti-tamper, environmental and general safety to ensure their readiness for worldwide operational employment. The Navy has no clear-cut guidance of determining whether an autonomous surface vessel is ready for deployment. Areas to be considered include COLREGS, physical and cyber security, and environmental/safety issues. US Fleet Forces Command is in the process of developing a Concept of Operations (CONOPS) for both Medium and Large USVs (M/LUSVs). Information from the draft version of that document was used to examine other autonomous entities (i.e., M/LUSVs), and have been (or are being) cleared for operational use. An unclassified autonomy certification checklist has been developed in the three primary areas (COLREGS, security, and safety) for use prior to deployment of USVs. A standing CONOPS Development Team (CDT) should be established to review and refine the checklist periodically.

A master's thesis from the Naval Postgraduate School examined how the Sea Hunter MUSV will react to degraded scenarios. Their research used the Autonomy, Validation, Introspection, and Assessment (AVIA) simulation environment and found that although Sea Hunter's maneuvers were predominately COLREGS compliant, they did not consistently meet the standard of good seamanship. It also revealed significant vulnerabilities to the Sea Hunter that should be addressed prior to fleet integration.
Keywords: *unmanned surface vessels, USV, MUSV, MDUSV, LUSV, COLREGS, certification*

Background

The Sea Hunter-type Medium Displacement Unmanned Surface Vessel (MDUSV) – one in service, one under construction – transitioned, in FY20, from an ONR-funded concept demonstrator to a Fleet asset under the cognizance of Commander Surface Development Squadron ONE (CSDS1). The Common Unmanned Surface Vessel (CUSV) is programmed to achieve IOC in FY21 as part of the Littoral Combat Ship Mine Warfare Mission Package. Lastly, the Navy is budgeting for a near-future class of Large Unmanned Surface Vessel (LUSV), aka Ghost Fleet. All USVs, regardless of their size and mission, need to be capable of autonomous operation across the globe.

To achieve IOC and deploy, the Navy must be fully assured that these vessels are safe to operate and pose no hazard to other mariners sharing the world's waterways. Naval and Commercial vessels are subject to a broad array of national and international regulations to ensure that they are safe to operate. At this point, there is no consensus on how these standards will be adapted to support the certification of these USVs.

This research would assist the Navy in assessing the various legal and regulatory regimes and defining the best means of satisfying them, without unnecessarily burdening the operating forces or OT&E

community. Insights may be gained from examining similar certification concepts in place for existing military UAV programs, as well as commercial maritime industry efforts to develop autonomous ships.

In December 2019, US Fleet Forces Command issued a Task Message which, in part, established a CONOPS Development Team (CDT) for the US Navy's Medium and Large Unmanned Surface Vessels (M/LUSVs). A draft CONOPS document was issued for Flag Officer review in October 2020 with an expected final release in November 2020. The document was at the SECRET/NOFORN level, but most of the information was unclassified. The draft CONOPS contained information that would be of use answering the research questions for this effort.

Findings and Conclusions

1. Three faculty members participated in the M/LUSV CONOPS Development Team (CDT) to assist in developing CONOPS for both the MUSV and LUSV. The document is set to be signed and released in November 2020.
2. Data from the Concept of Operations (CONOPS) was gathered to use for certification criteria in the three primary areas: COLREGS, Security, and Safety, identified in the research questions. The document was written at the SECRET/NOFORN level, but most of the information was unclassified. Only the UNCLAS portion was used for this research effort.
3. A Master's Thesis by two NPS students (LT Anderson and LT Oberholtzer) used this research as a basis for their effort would be used to populate various portions of this document. The thesis was completed in June 2020 and titled "Sensor component vulnerabilities and their effects on maneuvering medium unmanned surface vessels (MUSVs)" (Anderson & Oberholtzer, 2020)
4. Data was analyzed and sorted into the three readiness areas (COLREGS, security, safety) with a fourth overflow (other) section for additional information.
5. Findings will be presented to the sponsor through, at a minimum of quarterly Internal Progress Reviews (IPRs).
6. Final deliverables: Executive summary of findings, Poster for display at NRWG 21 (April 2021) and for use by the sponsor with a summary of findings, Anderson/Oberholtzer Thesis (June 2020), Paper on research effort (background, methodology, analysis, findings), and Final IPR in October 2020 to discuss findings/recommendations with sponsor.

Recommendations for Further Research

- Per guidance from US Fleet Forces Command, "After promulgation, the MUSV and LUSV CONOPS will provide the core methodology and approach for COMUSFLTFORCOM and COMUSPACFLT claimancies to address strengthening MUSV and LUSV capabilities at the operational and tactical levels. The CONOP may continue to be updated as required in order to address future innovations and capabilities in the fleet" (Fleet Forces Command, 2019).
- Maintain the core of the Concept of Operations (CONOPS) Development Team and meet annually to periodically review the checklist and recommendations and update as required.
- Use of simulation tools such as AVIA (used by LT Anderson and LT Oberholtzer in their thesis) can be of significant utility in the area of Collision Regulations (COLREGS) testing and compliance. The LTs found several instances where Sea Hunter would not maneuver in accordance with COLREGS.

- An additional checklist to include items at the SECRET/NOFORN level could be an area of future research.

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NPS-20-N298-A: Assessment of Ghost Swimmer Performance in Shallow Water with Marine Growth and the Surf Zone

Researchers: Dr. Joseph Klamo, and Dr. Anthony Pollman Capt USMC Ret.
Student Participation: LT Katherine Irgens USN, and LT Gladys Anuat USN

Project Summary

This work evaluates the entanglement of two unmanned underwater vehicles (UUVs), in marine vegetation native to littoral environments, for relative comparison and assessment of propulsion mechanisms. Boston Engineer's GhostSwimmer propels itself using a bio-inspired flapping tail movement, while Hydroid's REMUS uses a traditional, open, propeller for propulsion. Identical experiments were performed using both vehicles; however, this report will focus on the REMUS vehicle experiments to avoid distribution issues since portions of the GhostSwimmer results are considered controlled unclassified information. A towing tank, populated with synthetic giant kelp and eelgrass, was used to simulate an underwater marine vegetation environment. The traditional UUV with an open, three-bladed propeller and cylindrical hull form designed to conduct underwater surveillance was used for testing. Two different types of entanglement tests were conducted. A vegetation density and constant speed entanglement test, conducted by changing the propeller speed and marine vegetation density, showed an increased entanglement risk for eelgrass, astern propulsion operations, and high vegetation densities. A lateral placement entanglement test, conducted by changing the marine vegetation's lateral location relative to the vehicle center line, showed an increase in entanglement risk for vegetation located close to the propeller and indicated a relationship between propeller diameter, vegetation location, and probability of entanglement. Recommended future work includes entanglement testing for UUVs with different body geometries, testing in the operating environment, further testing to explore the nature of entanglement mechanisms, and assessing devices or procedures intended to reduce entanglement risk.

Keywords: *entanglement, unmanned underwater vehicle, bio-inspired propulsion*

Background

The Department of Defense (DOD) uses UUVs for a growing number of missions including sea sensing and mine countermeasures (MCM) missions (Department of Defense [DOD], 2016). By 2025, the DOD plans to use them to support undersea warfare (USW) missions in shallow water areas where manned platforms cannot operate (DOD, 2016). Major barriers to UUV operations in these shallow water littoral areas include fishing nets and marine vegetation that can entangle, damage, and result in the loss of UUVs (Keller, 2010). Dealing with the marine vegetation portion of the problem is difficult for multiple reasons. One is that the exact location and extent of an underwater marine vegetation field is typically unknown. Another is that many different types of marine vegetation exist with some potentially being more likely to entangle a UUV than other types.

Two types of marine vegetation commonly found in the littorals are giant kelp and eelgrass. Giant kelp, which is native to shallow waters with a rocky seafloor (Rocchio, 2014), is commonly found in the coastal waters of North and South America, South Africa, Southern Australia, and New Zealand (SeaWorld Parks & Entertainment, n.d.). Eelgrass, which grows in large beds in bays, inlets, and estuaries, can be found in the North Atlantic (Cascella, 2019). Giant kelp and eelgrass are an entanglement concern for marine vessels, divers and swimmers transiting in the ocean (Snyderman, n.d.).

There is little publicly available research that has investigated the likelihood of UUV entanglement by marine vegetation. Most publicly available information about UUV entanglement deals with patents that address avoiding propeller entanglement. A few examples of these include a fishing net winding device designed to disentangle UUVs caught in fishing nets (Harbin Engineering University, 2016) and a concentric cutting assembly designed to cut fishing nets and other objects entangled on underwater vehicles (Wiggins et al., 2015). Currently, knowledge of UUV entanglement in marine vegetation is mostly anecdotal, but it does occur even though officially reported numbers are difficult to find. This makes the actual probability of entanglement in vegetation difficult to estimate. The risk of propeller entanglement in other types of marine objects, such as nets, is better quantified and suggests the magnitude of the entanglement problem. One study evaluated navigational threats to Korean naval ships caused by derelict fishing gear (DFG) such as nets and lines (Hong et al., 2017). Over a six-year period, it was found that the propellers or shafts of vessels were entangled in DFG in 2,386 cases. If marine vegetation entanglement is as likely as entanglement in DFG, then once UUVs start to routinely operate in shallow water, entanglement will become a serious issue.

The objective of this research was to identify parameters that affect the likelihood of UUV propeller entanglement in marine vegetation. This effort considered the influence that UUV speed and orientation, propeller angular velocity, marine vegetation density and configuration, and marine vegetation type had on entanglement.

Findings and Conclusions

This investigation was conducted in the towing tank at the Naval Postgraduate School. A commercially available, Hydroid REMUS-100 UUV was used. The UUV was attached to the carriage plate that runs along rails on top of the towing tank using a vertical sting and an adapter that restricted the surge, sway, heave, roll, and yaw motion of the vehicle. The UUV was operated in a tethered (non-autonomous) configuration at a constant propeller speed, heading, and depth. Synthetic marine vegetation was used in the towing tank to simulate real-world vegetation. Giant kelp was simulated using commercially available, single strand, three-foot tall synthetic plants that had 8 to 10 leaves per plant. Eelgrass was replicated using several synthetic plants that were each composed of twenty blades, each 36-inches in length.

We conducted vegetation density and constant speed tests to determine the risk of entanglement for four parameters: propeller speed, propulsion direction, vegetation type, and vegetation density. Our results showed that moving astern in eelgrass always resulted in entanglements while moving forward in giant kelp never resulted in entanglements. Moving forward in eelgrass or astern in giant kelp resulted in occasional entanglements with the likelihood for entanglement increasing for low speeds and high vegetation density.

We also conducted lateral placement tests to determine the impact that marine vegetation location relative to the center line of the vehicle, and consequently the propeller, had on the likelihood of entanglement. We examined vegetation offset to both port and starboard sides of the vehicle to explore if entanglement from one side occurs more often due to the rotation direction of the propeller. When operating at forward propulsion the giant kelp never entangled and the eel grass had a low probability of entanglement. On the other hand, when operating at astern propulsion, both giant kelp and eelgrass had a high likelihood of entanglement for marine vegetation when it was located along the center line. The likelihood of entanglement rapidly drops for both giant kelp and eelgrass when they are laterally located at least a propeller diameter away from the vehicle centerline.

Major findings from this work include: 1) eelgrass posed a greater entanglement risk than giant kelp, 2) operating astern propulsion posed a greater entanglement risk than operating forward propulsion, 3) there is a critical vegetation density above which entanglement becomes very likely, 4) marine vegetation located closer to the vehicle center line increases the entanglement likelihood, and 5) the presence of stern control surfaces appear to reduce entanglement.

Similar vegetation density and constant speed tests and lateral placement tests were conducted with the GhostSwimmer using both the synthetic giant kelp and eelgrass vegetation. The testing results are presented and discussed in appropriately controlled reports.

Recommendations for Further Research

Recommended future work includes entanglement testing for different unmanned underwater vehicle body geometries, testing in the operating environment, further testing to explore the nature of entanglement mechanisms, and assessing devices or procedures intended to reduce entanglement risk. The test facility provided limitations on vehicle speed. Propeller speeds above 1200 RPM were not tested due to the short length of the tank and stopping distance required. Propeller speeds below 600 RPM were not tested due to insufficient propeller thrust required to overcome the frictional forces imposed by the text fixture bearing system. Future testing at propeller speeds below 600 RPM would be interesting to see if the likelihood of entanglement would increase as the vegetation density decreased.

The effect of the stern planes at reducing entanglements could be used to guide future work on entanglement suppression devices. Fixed fins located slightly below the stern control surfaces could further reinforce the action of pulling the eelgrass down from the water surface and away from the propeller thus reducing the likelihood of entanglement.

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NPS-20-N309-A: Employing Machine Learning to Predict Student Aviator Performance

Researchers: Dr. Magdi Kamel and Mr. Brian Wood
Student Participation: No students participated in this research project.

Project Summary

For decades, naval aviation training has used the Navy Standard Score (NSS) as the primary means of overall student performance evaluation. Machine learning analysis of student aviator training performance data offers novel and more accurate methodologies than current methods for performance assessment. These methodologies include identifying students for attrition or remediation, as well as identifying optimal pipeline assignments. In this research, we apply machine learning methods to identify important predictors and develop prediction models of performance in primary, intermediate, and advanced flight training based on data from Aviation Selection Test Battery (ASTB), Introductory Flight Screening (IFS), and Aviation Preflight Indoctrination (API) training (Chief of Naval Air Training, n.d.). The data science methodology used for this research is based on the Cross-Industry Standard Process for Data Mining (CRISP-DM) (Vorhies, 2016). Research results indicate that ASTB scores for ASTB versions 3, 4, 5, and E, have little or no effect on predicting the graduation or non-graduation of student pilots in primary and advanced training. However, the number of flight failures and the Federal Aviation Association (FAA) exam score in IFS data, as well as the API NSS, are significant variables for predicting the graduation status in primary and advanced training. These results have important implications in reducing time-to-train, improving aviator quality, and reducing training costs related to student failure to complete training.

Keywords: *aviation training, Big Data, data analytics, machine learning*

Background

With the current shift within the Navy to new training management systems (i.e., Training Sierra Hotel Aviation Readiness Program [T-SHARP]), new methodologies for evaluating and predicting student performance should be examined. Specifically, machine learning provides an opportunity to better evaluate students by fully examining every indicator of performance throughout a student's training from subtest scores on the aviation selection test battery and test scores during initial ground school to each graded item on every flight event. This full integration of performance criteria will identify trends and patterns currently lacking in traditional methods. Specifically, it will provide a better overall evaluation of student success in training, which aviation pipeline will ensure the most student success, while highlighting those students needing remediation earlier, in order to provide additional resources.

Findings and Conclusions

The main purpose of this research is to provide a data-driven evaluation of student pilot performance to identify performance indicators of whether a student will be successful or not in training, what type of aircraft and training the student will be most successful, and how early in training can success or likely failure be determined. This will greatly assist Naval Air Training Command sponsor leadership in assigning students the most appropriate training pipeline, as well as identifying individuals for attrition earlier on in training, thus reducing training costs.

This research applies advanced statistical and machine learning methodologies and techniques to analyze training data at a more granular level than ever before accomplished. The study also attempts to connect individual-level student data from selection through training to fleet aircraft assignment, providing the opportunity to identify performance indicators and trends across the continuum of aviation training. The data science methodology used for this research is based on the Cross-Industry Standard Process for Data Mining (CRISP-DM) (Vorhies, 2016). The CRISP-DM process model includes six phases that address the main requirements for data mining. The six phases are undertaken in a cyclical and iterative manner and include: Business/Mission Understanding, Data Understanding, Data Preparation, Modeling, Evaluation and Deployment.

The results of the research indicate that ASTB scores for ASTB versions 3, 4, 5, and E, have little or no effect on predicting graduation or non-graduation of student pilots in primary and advanced training. However, the number of flight failures and the FAA exam score in IFS data, as well as the API NSS are significant variables for predicting the graduation status in primary and advanced training. These results have important implications in reducing time-to-train, improving aviator quality, and reducing training costs from student failure to complete training.

Recommendations for Further Research

In this research effort, we identified important predictors and developed prediction models of performance in primary, intermediate, and advanced training based on data from Aviation Selection Test Battery (ASTB), Introductory Flight Screening (IFS), and Aviation Preflight Indoctrination (API) training. While our methodologies and results provide a good foundation for future research, we recommend extending this effort to later stages of training by developing models to predict performance in intermediate and advanced training, as well as in the Fleet Replacement Squadron (FRS) based on said training. Analysis goals include determining the set of variables predictive of student performance in later stages of training; revealing trends and patterns which may indicate where and when remedial action is needed; and identifying which aviation pipeline a student will be most successful based on performance in preceding training.

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NPS-20-N309-B: Analytics of Aviator Training Performance

Researchers: Dr. Neil Rowe and Mr. Arijit Das

Student Participation: Abram Flores CIV

Project Summary

This project investigated patterns in the training data of Navy aviators to predict their success in training. With the help of the sponsor, we assembled a database from many sources of training data. This database covered 18,596 candidate and Naval Flight Officer candidates through their pretesting, classroom instruction, candidate training in generic aircraft, and candidate training in specialized aircraft. This data was a challenge to organize because it came from many sources with some incompatible formats. After standardizing the formats and fixing errors in the data, and aggregating flight-training records to a smaller set of average scores, we had 339 features for the candidates. We then correlated their features using both numeric-correlation and nonnumeric-association (class-characterization) methods. We identified six kinds of measures of success in the program and particularly focused on correlations involving those. We did confirm some early indicators of success and failure in the program, but the effects were small. We conclude that the Navy is doing a good job of identifying candidates likely to be successful.

Keywords: *training, pilots, aviators, performance, testing, prediction, database, classroom, regression, correlation, classes*

Background

Naval aviators require extensive training, and it is important that this be cost-effective. We were tasked to identify factors that led to success or failure of candidates in the training program. Training has eight phases. Candidates first take an Aviation Selection Test Battery (ASTB) covering cognitive ability, personality, and psychomotor skills; then introductory flight screening with both classroom activities and flight training; aviation preflight indoctrination in the classroom which covers basic aviation concepts; primary flight training; intermediate flight training; and advanced flight training which varies with the kind of aircraft the candidate has been assigned. Optionally they may have subsequent records of the Fleet Replacement Squadron (FRS). It is also useful to identify initial data for the candidates before ASTB, such as starting date and previous academic testing, which we label as data of a pre-phase. Most candidates are prospective pilots, but some prepare as Naval Flight Officers and take different courses at the later stages. It is only useful to compare an attribute of a candidate to an attribute at the same or later phase.

The data we used came from a variety of sources. Some of it was numeric like traditional test scores; some was numeric in a limited range, such as grades of 1, 2, 3, 4, or 5 on flight exercises; and some of it was nonnumeric, such as candidate race, previous flight training, and whether they had been given an exemption on a particular evaluation. Candidate names and other personally identifiable information were not included. After standardizing the data, removing obvious errors, and aggregating the sparse data, we had 339 attributes for 18,596 candidates, but there were still many missing attribute values for tests and exercises the candidates did not complete.

Previous analysis of this data was regression analysis. However, this does not distinguish well between strongly associated factors, so it is valuable to look at binary correlations between factors.

Our previous work (Rowe, 2012) provides some useful new approaches. This work examined records of carrier landings as graded by Landing Signal Officers. We were able to show the rate at which landing success and quality increased with experience, and we were able to correlate phrases in the comments on the landings with the degree of eventual success of the candidate.

Findings and Conclusions

The aviator data was provided in 143 Excel tables with mostly blank entries (nulls). We converted it to delimited text files to simplify programming. The candidate identification (ID) code was the best way to link tables, though this was missing for some records, to which we assigned our own. We standardized formats, e.g., for grades that were Y and N instead of 0 and 1. Some numbers out of defined ranges were eliminated. Null values for numeric attributes excluded them from attribute comparisons, but nulls for nonnumeric attributes were kept, such as a null for previous flight training, meaning that the candidate had no previous flight training.

The many records of the flight tests had many nulls for tests not given to the particular candidate. We summarized this data by averaging the scores of the same candidate on the same skills on the same curriculum. Then we averaged the normalized scores for each candidate for each skill in the curriculum. Normalized scores are standard practice and are obtained by dividing by the expected performance level. This reduced 143 tables to six summary tables, which we combined on ID codes into a single table of 1710 megabytes with 339 attributes.

We correlated each pair of columns to see the predictive power of each attribute; binary correlations allowed us to see redundancies in the data. Two numeric attributes were correlated using the standard Pearson correlation. Two nonnumeric attributes were correlated by measuring for each pair of values the number of standard deviations by which they occurred more often than by chance. A numeric attribute and a nonnumeric attribute were correlated by averaging the numeric attribute for every value of the nonnumeric and measuring the number of standard deviations by which these averages deviated from the overall average for the numeric attribute. Correlations were always from the attribute for the earlier phase to the attribute of the same or later phase, since we were trying to predict the latter.

We correlated all 339*338/2 = 57,291 attribute pairs to test for redundancy among the factors and made a list for the sponsor. However, certain attributes were especially important to the sponsor as they indicated success or failure of a candidate, and we created a special output file for these. These were the final syllabus status, the STATUS attribute in the FRS data, counts on NSS (unsatisfactory) markings, average grades on flight tests, and whether we had data on the later phases for the candidate that indicated they had not finished.

Our results found several factors helpful in predictions, but all the effects were weak. We did not see any obvious factors in performance that the Navy is not acting upon. What factors we measured as significant, such as pre-Navy flight training and gender, are not ones the Navy can control practically or legally. Overall, we conclude that the Navy is doing a good job predicting performance of candidates by their multistage testing program.

Recommendations for Further Research

Much data on pilots was incomplete, and more could be discovered if records were kept more systematically. Future work could investigate additional metrics for predicting performance by additional testing. Combinations of factors could however show new trends. Our approach of combining factors to optimize statistical significance is promising and should be explored further.

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HQMC Aviation (AVN)

NPS-20-M155-A: Define the Requirements and Develop a Tool to Simulate and Visualize Own Force Technical Signatures within the Electromagnetic Spectrum

Researchers: Mr. Steven Iatrou, and Dr. Douglas MacKinnon
Student Participation: Maj Matthew Bowman USMC, and Maj Jacob McIlwain USMC

This research is an effort to develop methods for incorporating visual representations of risk into the US Marine Corps' signature management (SIGMAN) planning process. The research examines threats posed to operations security that have emerged from advances in electromagnetic spectrum (EMS) emission detection and classification and proposes methods for improving the planning process to mitigate these threats. The focus is on two significant operational areas: littoral operations in contested environments (LOCE) and expeditionary advanced base operations (EABO).

The study incorporates an examination of the technical aspects of the operational environment to account for own-force emissions in the EMS and the detection capabilities of sensors external to friendly forces. The objective is to create options for standardizing the current ad hoc process of assessing the risk posed by increasingly sophisticated means of detecting and classifying emissions into the EMS. This analysis establishes an EMS signature management framework that improves the commander's ability to understand the electromagnetic environment in the context of protecting operational and tactical maneuvers in order to mitigate threats to mission success.

This report proposes the application of a sense, understand, maneuver (SUM) process for assessing and responding to vulnerabilities posed by signature detections. The result of this process being a structured report on the signature, threat, risk to OPSEC, narrative, and gains from mitigation (STRONG report).

A visual representation of risk based on the SUM process and the STRONG report will provide commanders with a common framework for understanding risks posed by their own-force EM signatures in the context of the opponent's ability to detect and act on the information.

Keywords: *operations security, OPSEC, electronic warfare, EW, electromagnetic maneuver warfare*

Background

The US Marine Corps' 38th Commandant's Planning Guidance highlights the ever-increasing threats posed by opponents' abilities to detect and classify friendly force emissions in the electromagnetic spectrum. Naval force ability to physically maneuver in a contested environment depends on decreasing an enemy's ability to detect and anticipate friendly force actions. The distributed nature of modern warfare introduces new challenges to managing the unclassified but detectable actions of military actions, particularly in the EMS; the means for adequately managing emissions into the EMS begins with well-established force planning prior to operations.

A literature review of current US military doctrine covering information operations in general (e.g., Joint Concept for Operating in the Information Environment) and OPSEC indicators in particular (e.g., Joint Publication 3-13 and the Electromagnetic Spectrum Superiority Strategy) revealed significant differences in approaches to managing and planning the electronic emanations associated with military operations. This was particularly evident at the tactical level of operations. Personal interviews with service members assigned to Information Warfare related billets were used to gather information on the technologies involved, the scope of the issues, and to inform the development of planning tools to help coordinate signature management tools across operational units. These data informed the development of suggested processes and means for establishing a common evaluation scheme for SIGMAN efforts.

Findings and Conclusions

This research was conducted to support HQMC DCI in developing tools to reduce an opponent's ability to predict Marine Corp unit objectives and movements. The tools were created based on data collected from the literature and interviews. For this study the data were organized into two broad categories: general operational risk assessment; and specific adversary, competitor, and potential competitors' detection and exploitation capabilities. These data were compiled and analyzed by Naval Postgraduate School students following interviews with personnel from the Marine Corps Information Operations Center (MCIOC), I Marine Expeditionary Force Information Group (MIG), 11th Marine Expeditionary Unit (MEU), and Marine Corps Spectrum Integration Laboratory (MCSIL). The findings were used to understand aspects of signature detection and exploitation in the context of recent significant geopolitical events involving US competitors. These were incidents where competitors searched for, identified, collected, or exploited available signatures to their advantage; the signatures in these scenarios were readily and publicly available through commercial technologies that have emerged in the 21st century. The results from the case study analysis were used to develop tools for improving the integration of SIGMAN visual risk representation in current and future operations.

The research suggests that a common methodology to assessing risk-in-context, labeled a sense-understand-maneuver (SUM) concept, would create a baseline for planning SIGMAN. This should be accompanied by a suggested standardized reporting procedure that provides specific details on the signatures, the threat, the risk to OPSEC, the narrative surrounding the action, and operational gains to be realized through mitigating actions (named a STRONG report); the details of this report could then be incorporated into existing visualization tools such as risk dashboards for assessing the impacts of SIGMAN actions during operations.

Recommendations for Further Research

Follow-on studies should incorporate the proposed processes and visualization tools in military exercises or war-game mock-ups to gain further understanding of how to effectively manage own-force electromagnetic signatures across large geographic regions and widely dispersed forces.

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NPS-20-M151-B: Shipboard Hydrogen Unmanned Aerial System Operational Analysis

Researchers: Dr. Anthony Pollman Capt USMC Ret. and Mr. Gary Parker
Student Participation: LT Joshua Hildebrand USN

Project Summary
This work proposes and outlines an approval process for employing hydrogen as a fuel aboard U.S. Navy warships. The work begins with an exposition of state-of-the-art hydrogen systems for air, surface, and subsurface use. Then, a summary of the relevant regulations for using hydrogen as a fuel is given. With these items informing the conversation, a process modeled after a standard systems engineering "vee" methodology is proposed as a way to frame the necessary actions to deploy hydrogen onboard ships. A case study for deployment of a notional unmanned aerial system (UAS) is presented to illustrate the use of the proposed process. The report ends with a recommendation to use the proposed process as a template to develop, test, and formalize the procedures for routinely using hydrogen as a Naval fuel. Without this level of commitment and formalization from the Navy, progress toward use of hydrogen as a fuel is unlikely. Note: The original proposal for this work included efforts to demonstrate the process, employ a hydrogen UAS on the deck of a warship, and gather preliminary operational data to help make the case for hydrogen. However, as proposed, the scope did not fit within program guidelines, and the effort was de-scoped to simply creating a process for deploying hydrogen aboard ships.

Keywords: *hydrogen, fuel cell, unmanned aerial system, UAS, unmanned aerial vehicle, UAV, fuel*

Background
Continuing research and development efforts to operationalize electric propulsion technology for airborne (Airbus, 2020), ground (Diamond, 2017), and maritime environments (Fannin, 2019; Sandia, n.d.) have concurrently stimulated research into mobile energy storage technology. Currently, all-electric passenger cars and buses have batteries, capacitors, fuel cells or a hybrid of these to generate the electrical power needed for the vehicle's motors (Callaghan & Lynch, 2005). The National Aeronautics and Space Administration has used hydrogen fuel cells to power manned spacecraft since the days of the Gemini and Apollo programs (Burke, 2003). After the 1973-1974 oil embargo against the United States, the Department of Defense began examining ways the DOD could contribute to the national strategic energy goal of independence from foreign energy (Center for Naval Analyses, 2017). Hydrogen offers certain advantages as a potential fuel due to its fundamental physical characteristics and relative abundance. There are, however, practical considerations such as hydrogen production capacity, distribution infrastructure, and cost that have acted as barriers to widespread adoption of a "hydrogen economy" in the civilian market (Committee on Alternatives & Strategies for Future Hydrogen Production & Use, 2004). Lingering concerns that date back to the Hindenburg disaster of 1937 about the safety of hydrogen has created an uneasiness with use of hydrogen as a fuel (Strickland, 2009). Concern for safety in the handling and storage of hydrogen has resulted in standardized procedures and safety guidance for hydrogen use in fixed and mobile applications. Conversely, advances in compressed gas storage and handling technology have made use of hydrogen in mobile applications feasible (Basile & Lulianelli, 2014).

Findings and Conclusions

A process to use hydrogen as a fuel aboard a ship should ensure that introduction, storage, and use is done in a way that fully considers the risks involved and prioritizes the safety of the ship and its personnel (Office of Chief of Naval Operations, 2019; U.S. Department of Energy Hydrogen Safety Panel, 2020). A process is proposed in this work that follows a modified systems engineering "vee" model (INCOSE, 2015) and starts with clearly identifying the underlying need. The term "hydrogen project" is used to refer to any actions to introduce hydrogen in a gaseous or liquefied state aboard a Navy surface vessel for a specific purpose. The process proposed herein is the same for both temporary or permanent hydrogen projects; however, the level of the approval authorities and organizations involved may differ depending on the exact nature of a project.

The need should only be a problem or shortfall whose possible solutions can only reasonably be satisfied by use of hydrogen. A stakeholder analysis should be conducted to identify the groups and individuals that have an interest in the hydrogen project and may have certain requirements or equities to consider in developing a solution. Possible solutions that satisfy project objectives and stakeholder concerns are developed and analyzed, ultimately resulting in a preferred solution. The recommended solution is documented in the Project Plan which includes a Project Safety Plan that presents a risk analysis and actions to be taken to minimize or mitigate the risks.

The key decision point in the process is a project approval briefing presented to the decision authority (typically the appropriate fleet commander) and the ship's commanding officer. A major part of the briefing is a presentation of the Project Safety Plan. The decision-maker weighs the project's expected benefits against the risks. If the decision is to proceed, the project team proceeds with the installation, integration, and testing actions in conjunction with ship's personnel. Necessary training is conducted, and a final certification that the project is installed and ready for operations is issued by the project team to the ship. The commanding officer can either accept the certification in which case the hydrogen project is ready to be used, or can reject the certification.

A notional case study is presented to illustrate the methodology discussed above. In the case study, the Sunfire UAS system is completely fictional and does not represent any system currently under development by the U.S. Navy. The notional Sunfire UAS is approximately the same size and has the same payload capacity as an MQ-8C unmanned helicopter, but it is powered by hydrogen fuel cells versus conventional aviation fuel. The Sunfire's tilt-rotor design gives it a 15-knot advantage when in full forward flight over the MQ-8C, equating to a higher "dash speed" to travel from the launching platform to an operational area. The Sunfire Project Office at the Naval Research Laboratory now wishes to conduct operational demonstration flights from an aviation-capable surface ship under realistic operating conditions.

Recommendations for Further Research

The introduction of hydrogen aboard a U.S. surface warship can be a lengthy process depending on the exact nature of the hydrogen project, but there are definite regulations and codes that help ensure the introduction process is done in a thorough and safe manner. The U.S. Navy is no stranger to the use of potentially harmful or explosive substances onboard its ships. Operational risk management is the key to identifying hazards, accepting the appropriate level of risk, and managing the potential hazards onboard the ship and at pier-side. Ultimately, any process selected should have flexibility and should be tailored to meet the circumstances of specific projects. The investigators recommend that the U.S. Navy adopt the methodology outlined in this report as an initial template for introducing hydrogen aboard warships. Once a demonstration has been implemented, the investigators recommend using any of the lessons learned to inform creation and approval of a Naval instruction for use of hydrogen as a fuel aboard ships.

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NPS-20-M151-C: Removing Barriers to Hydrogen Use on Shipboard UAS

Researchers: Mr. Alan Howard and Mr. Brandon Naylor
Student Participation: Mr. Nico Alfaro CIV INT

Project Summary
Hydrogen gas and fuel cells are potentially valuable sources of energy for unmanned vehicles (UXVs), but they are difficult to use in a maritime environment due to a lack of standards and adopted use practices. Hydrogen is an attractive fuel source for UXVs because it is lightweight and more energy-dense than batteries and can be extracted from ambient moisture, provided there is a source of energy to supply the process of extraction. Despite its many potential benefits, there is limited precedent for hydrogen use while at sea due to the prevalence and low cost of conventional fuels. This study sought to explore the path towards the acceptance and adoption of hydrogen fuel use on surface ships in order to power deployed unmanned systems. This involved an in-depth review of the current standards and practices for storing, handling, and using hydrogen at sea and ashore. Our study found that while there are various small-scale demonstrations setting precedents for using hydrogen as fuel at sea, and a wealth of standards and practices for handling hydrogen on shore, these standards do not necessarily apply in full to Navy and Marine applications due to the differences in the ways the fuel would be produced and used. Therefore, the Navy and Marines must develop their own standards for generating hydrogen at sea, though existing commercial practices and hardware may inform the standards and practices for storage and deployment of hydrogen-based systems.

Keywords: *Hydrogen, H2, standards, practices, fuel cell, UXV, UAV, unmanned systems, energy, fuel*

Background
In a shipboard environment, use of hydrogen gas and fuel cells would be particularly beneficial because a ship could theoretically use excess power from their turbine generators to power a hydrogen extraction process to collect fuel for UXVs, simplifying the logistics chain for deployed UXVs. Hydrogen fuel may also be more permissible in a shipboard environment than lithium batteries because of concerns regarding the batteries' volatility, though hydrogen comes with its own set of safety concerns due to its nature as a flammable gas under pressure. This project set out to document existing standards and practices for using hydrogen onboard ships and discover a path to adoption and acceptance of hydrogen as fuel in a Navy shipboard environment. In doing so, we conducted a literature review of existing standards and practices for hydrogen use in commercial applications including maritime use and industrial applications on shore. The research team was also able to bring in a world-renowned expert in hydrogen safety and applications to give a seminar at the Naval Postgraduate School (NPS). The literature review and seminar informed a brief analysis on the future of hydrogen use in shipboard environments and the challenges facing full adoption.

Findings and Conclusions
To gain a reference point for the state of the art of hydrogen gas use in industry, the research team referenced various hydrogen and fuel cell demonstration projects in commercial sector maritime applications. The small boat demonstration projects and feasibility studies concluded that large scale hydrogen-powered vessels would be uneconomical, and the research team concluded that such vessels

would not necessarily be relevant to this study. The small-scale demonstration vessels were sufficient proof of concepts for the safe use of hydrogen as fuel on board surface ships. The research team also brought in Dr. Jay Keller, President and CEO of Zero Carbon Energy Solutions to give a talk at the NPS Defense Energy Seminar on the viability, safety, and myths surrounding hydrogen and its use as fuel. In his talk, Dr. Keller highlighted various hydrogen demonstration projects, addressed various safety concerns, and debunked some of the misconceptions regarding the nature of hydrogen (2020). It became clear that there was no consistent framework for standards and practices for handling hydrogen in a maritime environment, but the emergence of liquified natural gas (LNG) shipping has created an evolving set of standards and practices for handling a gas with similar properties (e.g., flammable, under high pressure). There are also established practices and policies created by organizations such as the Occupational Safety and Health Administration (OSHA) for handling hydrogen in industrial environments. The research team consulted the documented standards created by OSHA and for handling hydrogen gas and LNG to get a sense for what existing standards from other organizations might inform the development of a framework for the safe handling of hydrogen on ships.
Small boat hydrogen demonstrations currently rely on hydrogen fueling stations on shore to resupply, so there is not yet a common standard for hydrogen generation from other power sources while at sea.

Given the lack of demonstrated hydrogen generation at sea, the Navy and Marines may be required to adopt and adapt existing and developing OSHA and commercial standards for hydrogen generation, storage, and handling in industrial environments. For powering unmanned systems, the optimal path forward will continue to change over time. In the near term, batteries may be easier to deploy than hydrogen-based systems, since there is already a thorough history of battery-operated systems at sea. The growing market for LNG transport may also lead to the development of more general practices for handling flammable gas under pressure on ships, but these standards will likely not include practices for the generation or extraction of hydrogen from ambient air or water while at sea. Likewise, the Navy and Marines may have to develop their own practices for generating hydrogen while at sea, but standards and practices used on small commercial ships and on land can be used to set a precedent for safe hydrogen use and storage on ships.

Recommendations for Further Research

There remains a great deal of work in laying the groundwork for drafting and adopting a set of standards and practices for generating hydrogen on ships, not just using it as fuel delivered in port. This study was not able to accomplish all we had originally set out to do, due in large part to circumstances caused by COVID19. Using the commercial standards as a guide, work remains in drafting Navy and Marine-specific standards regarding hydrogen use. This will require a deeper dive into what specific equipment will be used to generate and store hydrogen on ships, and how it will interface with the unmanned platforms using the hydrogen fuel. This work will benefit from the continual development of commercial and industrial hydrogen standards and practices as more successful small-scale demonstrations of hydrogen fuel are seen around the world.

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HQMC Deputy Commandant Information (DCI)

NPS-20-M157-A: Objective Network for Operating with Resilience in a Contested Environment

Researcher: Dr. Alex Bordetsky, Mr. Steven Mullins, and Mr. Eugene Bourakov
Student Participation: Maj Andrew Walker USMC, Capt Haley Nowak USMC, Capt Samuel Wood USAF, Maj Michael Kennedy USMC, Maj Michael Tucker USMC, LCDR Ayman Mottaleb USN, LCDR Tommy Frye USN, LCDR Shonda Holloway USN, LCDR Christopher Jennings USN, LT Robert Hortaleza USN, LT Mark Villa USN, and LT Mark Zirion USN

Project Summary
In order to address the emerging Distributed Maritime Operations critical task of Operating with Resilience in a Contested Network Environment, the project team of Information Sciences (IS) Department students and researchers explored the characteristics of control channels for United States Marine Corps (USMC) novel Objective Networks via class research projects, thesis research and designed and conducted limited field and laboratory experiments. These efforts worked towards an end-state network which does the following: adapts to conditions, optimizes performance, and reduces detection/vulnerabilities, and leverages the cognitive domain where enterprise and local resources feed critical thinking to drive decisions, command, information, and operations. Taken together, these studies explored and demonstrated good potential for self-forming control channels and network operation services as a novel concept with high potential to help maintain resilience of tactical mesh networks, which support USMC operations in contested environments.

Keywords: *resilient networks, contested environments, adaptation to conditions, reduced detection, orbital and underwater control links, network management data*

Background
To maintain the continuous flow of Objective Networking research deliverables the Command, Control, Communications, Computers (C4) Headquarters, Marine Corps (HQMC) Deputy Commandant for Information (DCI) sponsor suggested starting the research process by leveraging class projects from network classes with high Marine Corps student participation, such as IS4505 - Tactical and Wireless Networking, IS4926 - Network Operations Centers, and master thesis projects at Center for Network Innovation and Experimentation (CENETIX). The sponsor requested that Dr. Bordetsky organize students and faculty to provide tangible deliverables for this research in the form of class project reports, lessons learned from field experimentation, and thesis research studies.

Findings and Conclusions
We conducted class research projects, thesis research, and designed and conducted limited field and laboratory experiments, accomplishing the following results:

1. Maj Andrew Walker, in his master's thesis (2020), collected critical data and demonstrated proof-of-concept solutions for aerial self-forming control architectures, based on hyper-node analytics and short living control links.
2. Capt Haley Nowak, in her master's thesis (2020), conducted experiments to create control channels capable of transferring tactical messages, by using burst LED links between underwater nodes, and extend above surface.

Note: The aforementioned breakthrough thesis studies were made possible through the creativity and outstanding support of CENETIX researchers, Mr. Eugene Bourakov and COL Steve Mullins (ret), IS PhD Candidate.

3. Maj Walker and Capt Nowak teamed with Capt Sam Wood to produce an IS 4926 class research project, which provided analysis of the most critical control variables captured in Simple Network Management Protocol Management Information Base format, and exchanged across the experimental self-forming control links (Nowak et al., 2019).
4. LCDR Ayman Mottaleb, Maj Michael Kennedy and Maj Michael Tucker, in their IS 4505 Class project (Mottaleb et al., 2020) explored Littoral Objective Network management from the C2 and technical perspectives, by designing potential network controls in contested maritime-land environments.
5. LCDR Tommy Frye, LCDR Rashaunda Holloway and LCDR Christopher Jennings extended Capt Nowak's thesis study results by considering Unmanned Underwater Vehicle (UUV) options for maintaining Objective Network resiliency. They explored UUV-augmented resilient networks in the environment of harbor surveillance and inspection (Frye, et al., 2020).
6. The team of LT Mark Villa, LT Robert Hortaleza and LT Mark Zirion took the Objective Network study into the Low Earth Orbit (LEO) domain. The team studied new network management scenarios in their IS 4926 class project (Villa et al., 2020), based on a CENETIX breakthrough initiative of extending tactical network control channels into the orbital domain by means of USMC-owned CubeSat nodes.
7. The CENETIX team expanded the Naval Postgraduate School (NPS) tactical networking testbed by creating a LEO CubeSat Node. CENETIX submitted a competitive proposal, to include a payload aboard a DREAM launch, during the maiden flight of a Firefly rocket. Upon receiving the award, the CENETIX team implemented a Cooperative Research and Development Agreement between Houston Mechatronics, AeroVironment, and NPS to produce a Cubesat with an Objective Networking Control channel payload, and began the multi-team effort. Marine Corps Warfighting Laboratory (MCWL) and 1Marine Expeditionary Force assisted the CENETIX team with experiment planning and the Navy-Marine Corps Spectrum Center (Maj Jeffrey Walker, Capt Nicholas Reed, GySgt Jesse Perard, CWO3 Moe Collins) also supported. The Cubesat, named NPS CENETIX Orbital-1, is now in the late stage of completion and its control channel payload flying permissions are now under consideration with the Navy-Marine Corps Spectrum Center for approval.

Altogether, these studies explored and demonstrated good potential for self-forming control channels and network operation services as a novel concept, with high potential to help maintain resilience of tactical mesh networks that support USMC operations in contested environments.

Recommendations for Further Research

Our primary recommendation for future research is to establish an experimentation campaign with the help of Command, Control, Communications, Computers (C4) Headquarters, Marine Corps (HQMC) Deputy Commandant for Information (DCI) and Marine Corps Warfighting Laboratory (MCWL), for the systematic experimental field studies of resilience across multiple domains, from underwater-to-orbit.

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HQMC Installations and Logistics (I&L)

NPS-20-M013-A: Modeling, Simulation, and Experimentation to Examine and Improve Combat Active Replacement Factors (CARF)

Researcher: Dr. Alejandro Hernandez COL USA Ret.

Student Participation: CPT Alexandre Anderson USA, CPT Casey Close USA, MAJ Chad Frizzell USA, MAJ Minou Pak USA, and MAJ Joshua Peeples USA

Project Summary

This effort explored the utility of combat modeling and simulation to generate Combat Active Replacement Factor (CARF) estimates for High Intensity Conflict in the absence of historical data. Using data generated from a designed experiment performed using the Synthetic Theater Operations Research Model (STORM), we demonstrated a repeatable and transparent method for generating CARF estimates. Using the STORM-based CARFs as the starting point, we developed a process to construct a "Model-Computed CARF" (MCC) for principal end items not explicitly represented in STORM. We compared the CARF estimates based on the STORM data to the CARF estimates generated by the legacy CARF Statistical Analysis Tool (CARF-STAT) and examined the difference in CARF estimates using STORM's two categories of loss, total and non-repairable. Additionally, this effort explored the use of an analytical model to understand the appropriate levels of war reserve materiel. Applying a systems engineering approach, a student team modified the classic news vendor model to analyze the appropriate inventory levels using marginal cost and marginal benefit concepts. The combined results of these efforts demonstrated the utility in using analytical models and constructive simulations to support CARF

estimation.

Keywords: *bootstrap forest, combat active replacement factor, forecasting, logistics planning factors, modeling and mimulation, Newsvendor Model, random forest, risk assessment, Synthetic Theater Operations Research Model*

Background

The Marine Corps uses a planning factor called a CARF to inform the quantity required to keep forces up to Table of Equipment (T/E) level if assets are destroyed or lost in an operation or contingency. CARFs, therefore, play a vital role in specifically estimating the Marine Corps War Reserve Materiel Requirements (WRMR) and ultimately informing the Authorized Acquisition Objective.

CARFs are currently calculated based on historical loss data from Operation Iraqi Freedom and Operation Enduring Freedom, which limits their range of reliable application to high intensity/ peer-to-peer conflicts. The Marine Corps has used a methodology based on a simple linear projection from the light and middle intensity conflict CARFs to estimate high intensity conflict CARFs. However, this estimated equipment attrition rate is not informed by modern adversarial capabilities or dynamics of combat.

Previous studies on WRMR include a Naval Postgraduate School (NPS) thesis (Solano, 2012), 2010 Operations Analysis Directorate (OAD) study establishing CARF formulas, a 2012 Installation & Logistics CARF Statistical Analysis Tool (CARF-STAT), and a 2019 OAD study that investigated the use of the STORM, a stochastic campaign model, to support CARF estimation. Previous studies have recommended pursuing combat modeling to support High Intensity Conflict CARF estimation, and the 2019 OAD study represented an important step towards that end.

In FY19, the NPS Simulation Experiments & Efficient Designs Center teamed with Group W to create a repeatable, transparent process for generating CARF estimates based on STORM loss data. This process included the design, execution, and analysis of STORM runs for a selected base scenario. NPS designed and applied a small design of experiment on the base scenario to induce reasonable variability, thereby ensuring that CARF estimation was not based on a very narrow set of circumstances. The inherent variability of STORM produced results that varied over repeated runs of the same scenario file, resulting in a distribution of CARF estimates for each STORM principal end item.

Our research objectives were to (1) explore the use of additional predictors for computing high intensity CARFs using a bootstrap forest technique; (2) compare each STORM-based CARF to its equivalent Table of Authorized Material Control Number (TAMCN) in CARF-STAT; (3) explore differences in CARF estimates based on using STORM's total non-repairable losses versus STORM's total losses; and (4) demonstrate the utility of an analytical model to understand war reserve management.

Findings and Conclusions

Using STORM based Combat Active Replacement Factors (CARFs) from the 2019 study as the starting point, we developed a process to construct a "Model-Computed CARF" (MCC) for end items not represented in STORM. Like the CARF Statistical Analysis Tool (CARF-STAT) methodology, we employed the machine learning method called the bootstrap (or random) forest, but used different predictors. Additional predictors were related to how the TAMCN is distributed among combat forces and included whether or not the TAMCN is considered mission essential by unit type and the proportion of a unit type's T/E. We trained the bootstrap forest using the STORM-based CARFs and generated a prediction for a sample of 752 TAMCNs not directly represented in STORM.

We compared the STORM-based CARFs to the CARFs obtained using CARF-STAT. Since a distribution of STORM-based CARFs is obtained for every end item, we compared the maximum STORM-based CARF to the corresponding CARF-STAT value. A planner who is risk averse with respect to a particular end item, perhaps because of the mission criticality of the item and/or the fact that it may be difficult to obtain from the industrial base in a timely manner, may decide to use the maximum value of the distribution of STORM-based CARFs. The overall trends were that (1) the maximum STORM-based CARF was larger than the CARF-STAT value for weapons and combat vehicles but (2) lower than the CARF-STAT value for logistics items. These results suggest planners should consider whether or not logistics systems are expected to receive damage.

By comparing CARF estimates based on STORM non-repairable loss to those using total loss, we obtained a distribution of differences that ranged from .02 to .75 with an average of .11. One interpretation is that approximately 11% of the equipment was offline, awaiting repair due to damage. However, the model did not account for items being offline due to scheduled or unscheduled maintenance.

We concluded that there is utility in using combat simulation to generate high intensity CARFs, though the process requires a significant investment in time and funding to generate the estimates for other scenarios.

Examination of the baseline newsvendor model showed the utility of an analytical model to understand war reserve inventory management (Anderson, et al. 2020). The team identified changes to the newsvendor model for its application in a military setting where there are only costs associated with inventory overage and shortage. To improve future application of the modified newsvendor model, the team designed a data collection form to help quantify the operational costs for having an inadequate level of inventory. Using the BA-5590/U battery, the team applied the model and illustrated the sensitivity of the optimal number to the variables in the cost parameter.

Recommendations for Further Research

The current Combat Active Replacement Factor (CARF) Statistical Analysis Tool (CARF-STAT) depends on commercially licensed and proprietary software. It may be beneficial to develop CARF-STAT 2.0 which utilizes open-source software (such as R or Python) and combines the predictors for the bootstrap forest algorithm into a larger set. Going forward, it may be useful to include predictors for a Table of Authorized Material Control Number (TAMCN) as being "a part of" or "always employed with" another TAMCN as part of a system.

Given there were a relatively small number of TAMCNs that were modeled in the Synthetic Theater Operations Research Model (STORM) scenario and its variations, exploring the use of a higher-resolution model such as Combat XXI would provide a larger sample of model-generated losses, which could then be used to compute a Model-Computed CARF (MCC). However, this approach likely entails as much investment in time and funding for the requisite modeling effort as does the STORM modeling, but with the advantage that a presumably larger set of MCCs could be computed directly from the combat model.

Lastly, we used the bootstrap forest machine learning technique to compute MCCs for TAMCNs not explicitly modeled in a STORM scenario. Other machine learning techniques such as rule-based methods and support vector machines to compute MCCs should be considered. Incorporating subject matter expertise may provide additional data to supplement these techniques.

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HQMC Manpower and Reserve Affairs (M&RA)

NPS-20-M165-A: Marine Corps Recruiting Command Officer Screening Team (OST) Location Optimization

Researchers: Dr. Daniel Reich, and Dr. Marigee Bacolod
Student Participation: CPT Brent Ogden USMC

Project Summary

We present a spatial analysis of Marine Corps officer recruiting with respect to diversity goals. We visualize the alignment between the current locations of Officer Selection Stations (OSS), Qualified Candidate Populations (QCP) and universities where dense groups of those candidates may exist, including historically black colleges and universities. We present three findings: (1) the current OSS Structure may not be optimal for maximizing recruiting of black officers in the southeast; (2) top universities and counties identified by QCP receive adequate coverage and officer accessions; and (3) the MCRC structure covers the top 1% black female universities by QCP less than the overall female QCP top 1%.

Keywords: *Optimization, Qualified Candidate Population, Recruiting*

Background

The Marine Corps has historically classified Marines by gender and race: as either male or female and either white, black, Hispanic, Asian and Pacific Islander, or other (Marine Corps Recruiting Command [MCRC], 2016). The Department of the Navy and the Marine Corps have employed various initiatives and efforts to increase the numbers of female and black, Hispanic, Asian, and other (non-white) Marine officers since at least the 1990s and have repeatedly fallen short of stated goals (Walker, 2011). In this study, we present a spatial analysis of Marine Corps officer recruiting with respect to diversity goals. We visualize the alignment between the current locations of Officer Selection Stations (OSS), Qualified Candidate Populations (QCP) and universities where dense groups of those candidates may exist, including historically black colleges and universities (HBCU).

Findings and Conclusions

We obtained records from the MCRC on officers who were recruited into the Marine Corps from 2006 to 2018. Available data fields included gender, race, and home of record address (city, state zip). After preprocessing out records that did not contain complete information, we were left with 47,826 officers in the data set. We developed a Python computer program to map these records to latitude and longitude coordinates, which were then rounded to a lower precision to anonymize the data and remove any personally identifiable information. We also obtained geospatial information for all the OSS locations. Using Tableau, this information was plotted and filtered to provide informative spatial visualizations.

Finding 1: The current OSS Structure may not be optimal for maximizing recruiting of black officers in the southeast. The concentration and wider geographical spread of black officers is unique amongst diversity categories in our data set. Other categories appear to be primarily concentrated in densely populated areas along either coast and/or in major urban areas. The concentration of HBCUs in the southeast U.S. yields a large pool of potential black officer candidates. However, only two of these schools are included in the Center for Naval Analysis (CNA) (Malone & Kelley, 2015) study's top 1% of schools ranked by potential officer candidates. None of the top 1% of schools from the male portion of the CNA study are HBCUs.

Finding 2: Top universities and counties identified by QCP receive adequate coverage and officer accessions. Of the top 1% or 15 universities for female QCP in the CNA study, all but three have an OSS location located in the same city. Each of the excluded three receive coverage within a 70- to 85-mile radius:

- University of Georgia is 72 miles from OSS Atlanta / 85 miles from OSS Kennesaw
- University of Wisconsin is 80 miles from OSS Milwaukee
- University of South Florida is 84 miles from OSS Orlando

Finding 3: The MCRC structure covers the top 1% black female universities by QCP less than the overall female QCP top 1%, when considering OSS locations in the same city and driving distances from a university to its nearest OSS location. Of the top 1% black female universities, 15 are identified and 5 do not have an OSS location within their cities:

- Florida Atlantic University is 45 miles from OSS Miami
- University of North Texas is 40 miles from OSS Dallas
- University of South Florida is 84 miles from OSS Orlando
- Southern Illinois University is 97 miles from OSS St. Louis
- Georgia Southern University is 127 miles from OSS Columbia

Recommendations for Further Research

Future study is required to quantify the potential impact of modifying the current locations of Officer Selection Stations (OSS). Visualizing the home of record locations of male black officers in the southeast

U.S. highlights a wider geographical spread and higher density in non-coastal and suburban/rural areas than is evident for other diversity categories tracked by the Marine Corps personnel records system. Overlaying historically black colleges and universities, of which none are included in the male portion of the Center for Naval Analysis study by Malone & Kelley in 2015, illustrates an opportunity to increase diversity in recruiting. Further mathematical modeling is needed to identify optimal placement of additional OSS locations, or relocation of existing ones. Another related analysis may focus on quantifying the ability to cover recruiting activities with fewer resources, including various scenarios for scaling down the number of OSS locations. If budget cuts are required at some point in the future, such analyses will be essential for developing effective plans to meet the overall recruiting requirements of the Marine Corps and maintain focus on increasing diversity in the officer ranks.

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NPS-20-M251-A: Data Collection and Analysis to Support a Limited Objective Test/Experiment (LOT/E) of a Billet Marketplace for Infantry Marine Officers

Researcher: Dr. Robert Koyak
Student Participation: Capt Andrew Malia USMC and LT Martin Nganga USN

Project Summary

The purpose of this part of the project is to determine how Marine officers perceive the current billet assignments process and to determine how those perceptions may affect their broader attitudes toward the Marine Corps. In this thesis, Captain Andrew Malia (2020) finds a strong association between dissatisfaction with billet assignments and a stated desire to resign from the Marine Corps at the next opportunity. The association remains even after controlling for the respondents' levels of satisfaction with the Marine Corps generally. The second line of effort is the development and implementation of a multi-objective assignment optimization model to run test experiments on the aviation community and draw recommendations. Lieutenant Martin Nganga's thesis (2020) develops two bi-objective models to produce non-dominated solutions to an officer assignment problem. The two objectives at stake are Marine preference and Permanent Change of Station (PCS) cost, though the framework is easily expanded to include others. Both models generate an approximated efficient frontier of non-dominated solutions,

which is a useful tradeoff curve for presenting alternatives. Our analysis strongly suggests that a billet marketplace will dramatically improve the Marine Corps' talent management in general and the officer assignment process in particular.

Keywords: *Marine Corps Officer Assignments, Marine Corps Billet Marketplace, survey analysis, multi-criteria decision making, Weighted Marine Assignment Model, WMAM, Hierarchical Marine Assignment Model, HMAM*

Background

The United States Marine Corps (USMC) assigns officers to billets to simultaneously balance the needs of billet owners, the career progression requirements for officers, and the officers' preferences. Currently, the Marine Corps relies on monitors to manually develop the assignment solution based on limited information about the Marine and the billet. This leaves the USMC with a suboptimal use of its resources and with officers whose human capital is not fully developed or who consider resignation.

Assigning Marines to billets requires attention to a combination of objectives. The primary objective is to maximize the warfighting effectiveness of the USMC in real time. A longer-term objective is to invest in the career paths of officers to give the USMC maximum realization of their value. Because achieving either objective is frustrated if officers decide to attrite for reasons related to their anticipated assignments, having officers achieve a high level of satisfaction with their assignments is also an important objective.

The purpose of a billet marketplace is to allow arbitrage between Marines, billet owners, and the institutional Marine Corps to obtain improved assignments with respect to a balancing of these prioritized objectives. The idea of combining input from billet owners, institutional stakeholders, and service members in a talent-management system is not new to the Department of Defense. It is incorporated in the Green Pages used by the Army; in the Career Management System-Interactive Detailing used by the Navy; in the Jetstream Detailing Marketplace acquired (but not yet fielded) by the Navy Explosive Ordnance Disposal community; and in the Talent Marketplace used by the Air Force. These systems give officers and enlisted service members an opportunity to state their preferences for open billets that they are qualified to fill, and they give billet owners a venue though which billet owners can learn about prospective movers. Marines have some input to the billet assignment process when monitors publicize upcoming billet vacancies and by giving Marines the opportunity to express interest in filling them, but this process is not systematic and can be improved in several ways.

Findings and Conclusions

Malia (2020) examines data from surveys recently administered by MMOA. From the MMOA Billet Assignment Survey administered in June 2019, approximately 38% of respondents expressed dissatisfaction with the assignments process. Malia finds a strong association between dissatisfaction with billet assignments and a stated desire to resign from the Marine Corps at the next opportunity. Using an innovative regression technique, Malia finds that the association remains statistically valid even after controlling for the respondents' levels of satisfaction with the Marine Corps generally.

Although these results do not prove a causal relationship between an officer's dissatisfaction with the assignments process and a desire to resign from the Marine Corps, they provide strong evidence that should not be ignored. Billet assignments cannot be made in a manner that is to the liking of every officer, but they can be made with greater transparency by adopting a billet marketplace system. Having a perception that the system is transparent, and that it incorporates input from the officers, can have tangible benefits for the Marine Corps, not only in the management of the system itself, but also in promoting good morale among its officers.

The current officer assignments process is heavily reliant on the capabilities of individual monitors to find a solution and from which it is difficult to optimize the multiple policy objectives outlined in the Marine Corps' orders. In his thesis, Nganga (2020) develops and computationally implements a prototypic, multi-objective assignment optimization model to run test experiments on the aviation community and draw recommendations. We see this as a first step to help MMOA adopt formal optimization in its decision-making process.

Nganga (2020) develops two bi-objective models, Weighted Marine Assignment Model (WMAM) and Hierarchical Marine Assignment Model (HMAM), to produce non-dominated solutions to a USMC assignment problem. The two objectives at stake are Marine preference and PCS cost, though the framework is easily expanded to include others. MMOA data were collected and processed to be used in our models, which are implemented using Pyomo software. The subset of USMC aviation community assignment problem tested includes 187 Marines that require assignments to 196 available billets. Both models generate an approximated efficient frontier of non-dominated solutions, which is a useful tradeoff curve for presenting alternatives.

Recommendations for Further Research

Our analysis strongly suggests that a billet marketplace would substantially improve the Marine Corps' talent management in general and the officer assignment process in particular. A billet marketplace would increase the quantity and quality of information available to the stakeholders. If prospective movers knew more about available billets they could form more accurate preferences. A billet marketplace would also give billet owners a reliable voice in the assignment process, which they lack in the current process. Because a billet marketplace automates information merging and optimization, not only would it improve the quality of the assignment solution, it also would free monitors to focus on aspects of the process that cannot be automated, including difficult cases and management of human relationships among stakeholders. Finally, the transparency and standardization of a billet marketplace would promote better morale. The level of satisfaction with the billet assignment process is directly related to an officer's stated desire to remain in the Marine Corps.

A shortcoming of the current officer assignment process is its inability to accurately measure its effectiveness. While Manpower Management Officer Assignments (MMOA) is capable of ensuring that the solution complies with manning and staffing guidance and other regulations, it is difficult for monitors to compare the assignments they made to alternatives. Future research could be fruitfully dedicated to more accurately measuring the effectiveness of past assignment decisions on officer performance in those assignments, on career progression and personal development among cohorts of officers, and on the retention behavior of individual officers.

Future research should continue translating the various managerial rules that monitors employ into the mathematical program to improve Weighted Marine Assignment Model (WMAM) and Hierarchical Marine Assignment Model (HMAM). A good candidate in this regard is consideration of Overseas Control Date. To the extent that the monitors have difficulty filling billets in units stationed overseas, those Marines with the earliest Overseas Control Dates are usually expected to fill those billets. Another candidate for improvement would be to include aspects of career progression. For example, a Marine who is coming from a B-billet should not usually be considered for another B-billet. The mathematical program could weight subsequent B-billets for such Marines sufficiently high to discourage those instances in the optimal solution, except in unusual circumstances.

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HQMC Plans, Policies & Operations (PP&O)

NPS-20-M117-A: MARSOC SOF-MAGTF Capabilities Integrations Analysis and Operational Modeling (Continuation)

Researchers: Dr. Robert Burks COL USA Ret., Dr. Jeffrey Appleget COL USA Ret., and CAPT Jeffrey Kline USN Ret.

Student Participation: LTC Delbert George USA, MAJ Nasser Aldowsary SA, LT William Reinike USN, AJ Derek Hirtz USA, MAJ Brad Young USA, LCDR Jon Turnipseed USN, MAJ Chris Arnold USAR, MAJ Romulo Dimayuga PI, MAJ Daniel Le USA, MAJ Kevin Chesnut USA, LT Jonathan Bermudez-Mendez USN, LT Ross Spinelli USN, MAJ Seon Lee USA, MAJ Julianne Zike USA, MAJ James Hyman USA, MAJ Matthew Radman USA, MAJ Jonathan Wood USA, MAJ Brandon Sirois USA, MAJ Garth McDermott USA, MAJ Tom Schlesinger USA, MAJ Joe Dywan USA, Capt Bud Geldmacher USMC, Capt Mike Lugo USMC, Capt William Wine USMC, and CW3 Richard Manley USA

Project Summary

This research built upon research conducted in FY19 and was worked in conjunction with ongoing Naval Postgraduate School (NPS) and Marine Corps Warfighting Laboratory (MCWL) efforts examining Expeditionary Advance Base Operations (EABO), and focused on exploring, assessing and identifying SOF-MAGTF capabilities integrations to improve current and future EABO and Distributed Maritime Operations (DMO) operations. The research leveraged the NPS Warfare Innovation Continuum (WIC) and multiple JCA and Wargaming Applications courses to develop its insights. It also analyzed and identified mechanisms that will allow Marine Corps Forces Special Operations Command (MARSOC) to better serve as a bridge for capabilities integration with SOF and deployed MAGTFs, to maximize the complementary capabilities of each formation. The effort was based on an exchange of ideas between MARSOC and NPS researchers to better understand current operational concepts and concerns, and identified six critical MARSOC issues for exploration. Specifically, it examined MARSOC, United States Marine Corps (USMC), and United States Navy (USN) cooperative missions in the South China Sea

through wargaming and analysis studies. The work's recommendations and findings directly support MARSOC in analyzing SOF-MAGTF capabilities integrations in a future DMO in order to examine its ability to shape the operating environment and deter peer adversaries throughout the contact layer while setting conditions to dominate in a conventional conflict.

Keywords: *Expeditionary Advanced Base Operations, EABO, Marine Air-Ground Task Force, MAGTF, Distributed Maritime Operations, DMO*

Background

Expeditionary Advanced Based Operations is an evolving USMC concept for 21st Century warfighting across the 2018 National Defense Strategy's Contact, Blunt, and Surge Layers of competition and conflict (Department of Defense, 2018). Additionally, the MAGTF concept is central to the way the Marine Corps mans, trains, and equips its forces in this environment, and it is one of the very fibers of the Corps' strength: it is the way the Marine Corps fights. Marines and SOF are naturally aligned in terms of mission approach and execution, as their forces are forward deployed in similar geographical areas, are actively engaged in shaping operations, can respond immediately to crises, as well as perform operations in a sustained campaign.

The wargames utilized in this work familiarized participants and observers with USMC and USN expeditionary capabilities, concepts for joint and coalition employment, and assessment of potential locations and logistics requirements for expeditionary operations. Under the NPS WIC construct, NPS student team mini-studies, conducted in the Joint Campaign Analysis course, informed and underpinned the design and conduct of further research into our research's six critical MARSOC issues. These mini-studies were followed by NPS faculty-advised student wargaming teams in the Wargaming Applications course, which designed, developed, conducted, and analyzed two wargames leveraging the findings from the mini-studies. The wargames modeled MARSOC actions in the Contact Layer by, with, and through indigenous Armed Forces of the Philippines (AFP) partners to secure advantages and deter Chinese influence, and to best posture MAGTF and other conventional forces in the event of conventional combat operations in the Blunt Layer.

This effort focused on gaining insights into the following five major issues:

1. What indirect opportunities exist to better succeed in the Contact Layer?
2. What actions can and should MARSOC take to capitalize on identified opportunities?
3. What indirect approaches in the Contact Layer could provide opportunities and advantages in the Blunt Layer and deter major conventional war?
4. What AFP partners are most effective and efficient for mission accomplishment?
5. What is the Contact Layer's risk assessment of indirect approaches/actions by MARSOC?

Findings and Conclusions

This effort resulted in the following findings and recommendations for each identified issue.

Issue 1: The Marine Special Operation Company (MSOC) is postured to conduct operational preparation of the environment and provide reception, staging, and onward integration assessments of infrastructure basing. During the inter-deployment training cycle (IDTC), MSOCs should become well-versed in

Theater Special Operation Command strategic and operational plans, Department of State (DOS) Integrated Country Strategy for the Philippines, and Enhanced Defense Cooperation Agreement (EDCA).

Additionally, per Marine Corps Forces Special Operations Forces 2030 (MARSOC 2018), MARSOC Leadership should attend the Special Operations Command Pacific (SOCPAC) annual planning conference during their IDTC and/or pre-deployment planning/meetings with SOCPAC, 31st Marine Expeditionary Unit (MEU), United States Seventh Fleet (SEVENTHFLT), and Planning and Advisory Training Team (PATT). This would better align efforts between SOCPAC entities; 31st MEU, SEVENTHFLT, Marine Corps Forces, and United States Indo-Pacific Command. This enables a larger return on strategic, operational, and tactical investments; ties these efforts with larger/long-term interagency and whole-of-United States government strategy; and nests efforts with AFP plans.

Issue 2: SOCPAC entities are not properly synchronizing operations, actions, and activities (OAAs) during the IDTC. Increased collaboration and preemptive planning with the PATT, 31st MEU SOFLE (Special Operations Forces Liaison Element), and SEVENTHFLT staff during the IDTC will better align OAAs, concept of operations, and theater-security cooperation events.

Issue 3: IDTCs and deployments need increased command, control, communication, and intelligence with MARSOC. We recommend 31st MEU personnel participate in MARSOC IDTC, validation of the 31st MEU SOFLE requirement, leveraging joint chief of staff and conventional exercises, and ensuring, prior to deployment, MSOC participation in the 31st MEU deployment readiness exercise.

Issue 4: Currently, MARSOC is too focused on counter terrorist (CT) efforts, the 31st MEU is too focused on contingencies and the Blunt Layer, and increased non-CT OAAs are necessary to adequately counter-revisionist states. Therefore, improving dialogue among SEVENTHFLT, 31st MEU, and SOCPAC will increase 31st MEU's contribution of capability and capacity in support of SOCPAC OAAs and the DOS integrated country strategy for the Philippines.

Issue 5: Leveraging MARSOC as a synchronizer, increased MAGTF capability and capacity will improve availability and influence conventional AFP joint task force and sub-component commanders. However, AFP joint conventional force relationships should be built with U.S. joint conventional forces, not strictly SOCPAC entities. As MSOC is not ideal for partnership with AFP sub-component commands, the 31st MEU should take on more partnerships with the AFP sub-component commands in the country, as SOCPAC entities do not have the capacity nor capability to take on these vital relationships for success in Phase 2+/Blunt Layer.

Issue 6: Although large joint combined exercises are a measure of deterrence and increase warfighting readiness compared to small exercises, their large operating footprints increase the vulnerability of collection by adversaries. Therefore, the location and timing of joint combined exercises should vary, as the advantages of conducting multiple combined joint exercises each fiscal year outweigh the counterintelligence and operational security threats.

Recommendations for Further Research

The Distributed Maritime Operations (DMO) and Expeditionary Advanced Base Operations (EABO) are two nascent concepts that will require further research to better understand how the United States Marine Corps and the United States Navy can use them to interoperate more effectively to establish and maintain sea control in any maritime environment. Essentially, these two concepts will need to mature through continued programs of wargaming and campaign analysis research, to best serve the U.S. Department of Defense.

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NPS-20-M236-A: Fire Support Coordination Cognitive Assistant (FSCn CA) for MAGTF Operations

Researchers: Dr. Arkady Godin and CAPT Scot Miller USN Ret.
Student Participation: Capt Benjamin Herbold USMC

Project Summary

A need has been identified to improve Fire Support Coordination (FSCn) processes between the Ground Combat Element (GCE) and Air Combat Element (ACE) within the Marine Air Ground Task Force (MAGTF). Proliferation of advanced technologies, increased operations in the littorals, and vast volumes of data seek to overwhelm the cognitive abilities of Marines in FSCn roles. In future conflict, a cognitive assistant (CA) functioning as a teammate will be required to reduce the cognitive load on decision makers integrating and deconflicting the battlespace. This requires a shared interpretation of data and information between the GCE Fire Support Coordination Center and the integral Direct Air Support Center of the ACE. To this end, the research objectives were applied to artificial intelligence (AI) to the FSCn information battlespace by performing data and information fusion to extract entities and events, followed by ontologies-aided reasoning. Our research also examined the development of an updated Observe-Orient-Decide-Act (OODA) loop with added sophistication in Situation Awareness (SA). FSCn personnel, due to managing several situations concurrently, require understanding individual situations' contexts and the contexts across all situations, therefore, our research identified SA technologies capable of adapting to changing and unplanned circumstances; this may have ramification of offering a novel way of doing planning for FSCn. Research deliverables include literature review on SA and mission context technologies, data architecture with descriptions of AI technologies, and a design of FSCn CA.

Keywords: *fire support coordination, SA, context, adaptive, situations, events, entities, courses-of-action, COA, workflow, deep learning, strategic, Observe-Orient-Decide-Act, OODA, situational awareness, SA, artificial intelligence, AI, reason, interpret*

Background
The historical background for the Fire Support Coordination Cognitive Assistant is limited, as it is a relatively new tool born during the era of AI. User Interfaces (UI) used for Intelligence Preparation of the Battlespace possess the capability of conducting 3D rendering of the physical battlespace, providing a promising starting point for the construction of the FSCn CA. Additional UIs, such as those used for ballistic missile defense and space operations, also seem promising due to their inherent ability to track entities with trajectories through the battlespace. The FSCn environment, a multi-domain battlespace combining the physical world and the trajectories of entities, serves as a combination of the earlier mentioned UIs. These technologies should be available in existing government off the shelf products. While current MAGTF FSCn manual processes have worked in the past, the nature of the battlefield and the character of warfare is changing. The introduction of technologies such as drone swarms, hypersonic missiles, unmanned fighter aircraft, and others, will convolute battlefield geometries and overtax current deconfliction and integration processes. Coupled with the vast volume and variety of information available through open-source intelligence and integrated sensor networks, the cognitive abilities of decision makers in FSCn roles are therefore, heavily taxed.

Findings and Conclusions
Our study explored the required functional processing of the analytical pipeline for a Fire Support Coordination (FSCn) Cognitive Assistant (CA). Therefore, FSCn tactical techniques and procedures-based processes were codified into workflows, which were then expressed in easy-to-use natural language. Next, workflows were visualized between humans and the FSCn CA teammate, to ensure the latter was seamlessly interfacing with the FSCn operators and higher approving authorities. Once we arrived at an infrastructure and solution, we proposed a model for the FSCn CA.

In addition, headquarters Marine Corps Plans, Policies & Organizations Deliberate Universal Need Statement (D-UNS) for FSCn CA emphasized that the central component – i.e., the heart – of FSCn CA machine cognition will be its Natural Language Processing/Understanding" (NLP/U) capability. As a result, our research team conducted deep investigation as to the most complex aspects of the NLP/U capability. We concluded it's not in the NLP/U area of extracting "physical" well-known entities, as United States Marine Corps has a high-confidence knowledge of the adversarial objects. The real complexity is in the NLP/U of the events. While the "extraction" technique which deals with "P" of the "NLP" is known quite well, complexity is on the "U" side. The first difficulty is encountered even when the meaning of the event is understood, as events are extremely diverse in semantics. There is no problem in the interpretation of events interacting with entities, as the meaning of such events is transparent due to the physicality of entity objects. The difficulty rises when events are associated with verbs at any level of abstraction. The higher the level of abstraction, the more difficult it becomes to do "U" processing. There is also a possibility of "unknown unknown" events, sometimes referred to as "black swans" as such events are not only unexpected, but are also "semantically unknown or unexplainable."

Building on the work of Dr. Endsley, a prominent Situation Awareness (SA) researcher who defined well-recognized "Endsley SA Model," our next findings are in OODA's "Orientation" phase, specifically in the Fusion combining observations (entities and events) with what D-UNS described as "Knowledge Representation" (KR). For our research team KR is bigger than just representing information about the world that is first presented to the FSCn CA as untagged evidence, but in the pre-processed form. KR also must represent innate knowledge that should be fed into the FSCn CA to understand the commonsense entities, events and logic. Our research shows that CA should use background knowledge prior to using, per D-UNS terms, "Automated Reasoning" and "Deep Machine Learning" techniques, based on, respectively, KR and Deep Neural Network technologies. Our research team concluded there is difficulty in generating not only a commonsense knowledge (which is an area of decades of research), but also in the fusion of operational observations, with background and commonsense knowledge at various levels of abstraction, as dictated by the semantics of the participating events in fusion processing operations.

Recommendations for Further Research

Further research with a focus on Mission Plan and Battlespace Decision Aid tools should be explored in the area with the highest return on investment. In general, this area is poorly explored and, therefore, remains on the cutting edge of research. However, while the decision-making process requires fewer events and entities, in reality, the number of events is very large. Therefore, there is a need to focus research on developing aggregation techniques, to reduce the number of events at different levels of abstractions across multiple domains. Other areas of research could be domain-specific, and focused on more abstract events, including states and actions for situations and situations transitioning. Lastly, most complex events are characterizing concepts, which are situations or situation patterns at the highest level of situations generalization. This makes events, which are heterogeneous in their nature of abstraction, difficult to aggregate. However, research in this area remains critical, as decision makers won't be able to scale over many events, or understand root-cause relations, in situations where this ultimate understanding is required to make fast and informed decisions.

NPS-20-M284-C: Context Modeling in Support of Non-lethal Weapon Rules-of-Engagement

Researchers: Dr. Anne Baylouny, Dr. Susan Aros and Dr. Steve Hall
Student Participation: No students participated in this research project.

Project Summary

This project investigated whether the U.S. Army's simulation software Athena could be integrated with the Naval Postgraduate School's Workbench for refining Rules of Engagement against Crowd Hostiles (WRENCH) crowd simulation software to the benefit of both. Athena is a multi-dimensional socio-cultural simulation program that has been under development for the past 20 years, most recently by the Jet Propulsion Laboratory, NASA. WRENCH remains in development, formerly under the direction of Dr. Steve Hall at NPS now under Dr. Baylouny and Dr. Aros. Athena incorporates over 100 variables and is a deterministic program, while WRENCH has stochastic features. The two operate on different levels of analysis. WRENCH focuses on individuals, social identity groups, and population behavior in interaction with security forces at the local level. Athena, on the other hand, simulates strategies on a regional or country level. Both levels are necessary to obtain a complete projection of potential outcomes. This project investigated whether the benefits of both programs could be integrated in order to simulate likely security force-population interactions for the purpose of refining new rules of engagement for the use of non-lethal weapons (NLW).

Keywords: *crowd behavior modeling, social identity dynamics, non-lethal-weapons, NLW, rules of engagement, ROE, Athena, Workbench for refining Rules of Engagement against Crowd Hostiles, WRENCH, security forces, simulation*

Background

The Joint Intermediate Force Capabilities Office has for several years been engaged in the development of WRENCH, a multi-agent crowd behavior model being developed under the guidance of Dr. Steve Hall at the Naval Postgraduate School. This model was designed to be of sufficient fidelity to support anticipatory analyses of likely civilian crowd behavioral responses to security force engagement actions. WRENCH is fundamentally intended to provide a means of refining the current processes employed in delineating the prospective rules of engagement (ROEs) which will be used in managing specific actions toward potentially hostile crowds. Specifically, WRENCH will support the generation and refinement of the ROEs that will govern the use of non-lethal weapons in particular circumstances, so as to achieve the immediately mandated tactical objectives while still maintaining the legitimacy of the wider-scoped governance processes.

At the heart of WRENCH is a multi-scale model of social identity dynamics. These dynamics are driven by both environmental conditions and the interaction between crowds and security forces. Social identities are a key determinant of the extent, intensity, and focus of any cohesive crowd behavior response and thus provide the crux of the anticipatory power of WRENCH. The influence of the environmental conditions on the emergence of potentially troublesome social identities certainly includes the broader spawning conditions under which the crowd was initially motivated to gather in the first place. However, environment also includes the immediate conditions surrounding the crowd.
These immediate felt or tactical conditions are generally more dynamic than the broader crowd-spawning conditions; thus, their dynamics must often be captured, and their influences modeled to successfully anticipate social identity dynamics. In situations of prolonged civilian or crowd engagements, these tactical environment dynamics mainly reflect changes in the broader environmental context. Even in short engagements between crowds and security forces, the tactical environment can evolve sufficiently during the engagement interval to become a significant driver of collective identity and response behavior. Athena Regional Stability Simulation software is a simulation modeling program supported by TRADOC (U.S. Army Training and Doctrine Command). Athena offers the promise of providing to WRENCH the required environment dynamics modeling without the need to replicate it in WRENCH proper. Reciprocally, WRENCH potentially offers to Athena a higher-fidelity model of the behavioral response that can be reasonably anticipated from a crowd's interaction with security force actions.

Findings and Conclusions

We proceeded to first review existing design documentation and cases which used Athena and WRENCH. We focused on code implementation, again examining overlap and looking for points of potential incorporation. We then identified which Athena output variables could dynamically update WRENCH and what if any transformation would be required before WRENCH could effectively use the Athena quantity. Our third step was to identify which WRENCH variables would be useful in dynamically updating Athena's environment model. We also examined what if any transformations would be required to make this dynamic integration. With this information we determined the best integration strategies. WRENCH and Athena could be integrated through several methods including: 1) A tight integration of the code bases themselves, 2) a formal application that could serve as an interface for the programs, or 3) an informal process with people manually integrating by turns.

Athena can replicate and trace all changes throughout the model over the entire simulation run, even being able to step back to any time-step of a completed run. Incorporating the stochastic elements of WRENCH would no longer allow for exact replication of a simulation run in the same way. Incorporating WRENCH's stochastic elements also means that using a single run to provide results for a given scenario would be the equivalent of using a single draw from randomly distributed simulation results as representative of all of the possible results for that scenario. Therefore, it would not be advisable to fully incorporate WRENCH into Athena.

WRENCH has been designed for smaller-scope scenarios that model details of crowd and force agents in a relatively small geographic area. This makes it difficult for WRENCH to model larger geographic areas or regions. Integration with Athena could enable multiple WRENCH models to simulate different neighborhoods in a single scenario. Athena can also provide periodic updates to the WRENCH model regarding political influences on need-statuses and thereby influence their intentions. Longer term economic factors affecting resources could be injected into the WRENCH models when dynamically integrated with Athena.

With Athena's broad scope, it necessarily cannot model the high level of detail that WRENCH can, particularly when it comes to individual and group dynamics. Integration of WRENCH would have enabled real-time injections into Athena in two important areas. First, integration would have allowed into Athena both behavioral changes by individual civilians in response to changes in their environment and the resulting impact on group attitudes from those environmental and behavioral changes. Second, it would have enabled real-time changes in Athena in terms of civilian group memberships, compositions, and intentions in response to changes in their environment.

WRENCH could have helped Athena by modeling force engagements with civilians. Athena does not currently model direct engagements between forces and civilian groups. Actual civilian-force engagements significantly impact needs and attitudes of the people and may cause casualties as well. Feeding this information from WRENCH into Athena in real time would allow for a more robust representation of the effects of forces on civilian groups.

Recommendations for Further Research

The simulation programs Workbench for refining Rules of Engagement against Crowd Hostiles (WRENCH) and Athena perform at different and complementary levels. Athena performs at the regional level while WRENCH is geared toward local, detailed interactions. A logical question is whether the two programs could integrate to the benefit of both. While dynamic integration between WRENCH and Athena is technically possible, such a project may be more time-consuming than valuable. Indeed, Athena is no longer being developed, and it is not clear if support for further changes would be forthcoming. Dynamic integration of the programs is complex and is projected to entail significant resources. To most efficiently utilize resources and time, we do not recommend integrating these programs. Instead, we recommend leveraging the strength of each program to enhance the initial scenario design for the other, as well as inform potential future improvements to the other simulation program. If there are opportunities to improve either program through further development efforts, we recommend drawing on the design strengths of each program to inform such improvement efforts. Since the Naval Postgraduate School has an ongoing project to further develop WRENCH, we could add Athena design elements in parallel to that effort. This would further inform WRENCH's development. In turn, WRENCH can be used to improve and expand Athena, if that effort were to continue. We recommend continuing the development of WRENCH with Athena programming in mind and examining potential updates to the Athena program itself in order to improve Department of Defense training and projection capabilities.

HQMC Programs & Resources (P&R)

NPS-20-M009-B: Software Development Now and in the Cloud – A Case Study

Researcher: Dr. Carl Albing, and Mr. Glenn Cook
Student Participation: Capt Amy Hsu USMC, and Capt Robert Patterson USMC

Project Summary
Government software development agencies are evolving as networks consolidate and security requirements tighten in the DoD. At the same time there is emphasis on migration to "the cloud" (external or internal service-based systems). How do the current practices within DoD compare to the state of the art in industry? What methodologies are needed for government software developers to continue supporting DoD systems? Does this change when software development and deployment move to the cloud? What challenges are faced when moving to the cloud? What are specific to the cloud environment? This study is meant to provide insights into the challenges as well as the advantages of such approaches and offer recommendations.

Keywords: *software development, cloud computing*

Background
Government software development agencies are evolving as networks consolidate and security requirements tighten in the DoD. There is a tension between development tools needed to develop software and their lack of security to be approved for use on the network. The underlying question is this: without development tools, can government software developers continue to support DoD systems? How are government software development agencies treating their development, test, and production environments, and what techniques are they using to migrate code in between? This study aims to produce knowledge of the current techniques employed to answer security concerns while enabling software developers to use modern tools. The result of the knowledge will be either: sharing of best practices between software development agencies or highlighting an emerging concern that must be addressed by the DoD and other agencies in the federal government.

Findings and Conclusions
After researching the possibility of using a cloud-based Integrated Development Environments (IDEs) for a python project, what we found can be summarized as follows:

- Most IDEs are based on local hosts (i.e., laptops, towers, etc.). Individually, each user could choose an IDE that works and project coordination would be handled via git source control.
- Of the few cloud-based IDEs, most require the use of their vendor-private cloud and storage.
- Cloud9 from AWS may come closest to being a general solution, but AWS has no plans to move Cloud9 to GovCloud (for at least a year, maybe longer), and thus may not be viable for DoD use.
- Eclipse Che (a cloud-based version of Eclipse) claims both single and multi-user support in the cloud, but it requires docker or other container technologies and its configuration will be at least as complex as that required for the existing cloud-based analytics environment. It is not a quick solution.

We looked at software development methodologies in general and then in specific at three DoD locations. More on that will be available in the final thesis from Hsu and Patterson. Furthermore, we considered the cloud and its possibilities and pitfalls for use as the next significant source of computing resources for the DoD. Through examining two specific scenarios we learned that there is much to be gained from the cloud, both from its scalability and from the consistent environment that it provides irrespective of the user's organization. But we also saw the need to adapt to a new vocabulary of vendor-specific jargon and potentially new concepts. Moreover, while there are many savings possible due to the scalable nature (down as well as up) of computing resources and a certain amount of vendor-supplied system administration, much of the administrative tasks, particularly for Iaas and PaaS scenarios, need to be borne by the customer. That is, system administration tasks do not go away.

Recommendations for Further Research

This work just begins the consideration of aspects involved in configuring and using cloud resources for software development. Many of the specifics that we have documented pertain more to the system administrators than to the developers, but they must be considered. Through all this, for end users, in-house system support, and leadership, and of primary importance throughout, is a recognition that the transition is non-trivial and requires some education and training in cloud technologies.

NPS-20-M163-A: Quantifying Enterprise Risk to Enable Portfolio Analyses Across the United States Marine Corps

Researchers: Dr. Kenneth Doerr, Dr. Erich Morman, Dr. Ira Lewis, and Dr. Chad Seagren Maj USMC Ret.

Student Participation: Maj Patrick McElroy Jr USMC and Capt Christopher Farhar USMC

Project Summary

In this paper, we pursued three tasks: (1) A systematic review of enterprise risk management (ERM) literature to assess the state of knowledge about public sector ERM; (2) An assessment of current risk metrics used by Headquarters Marine Corps (HQMC) Programs and Resources (P&R); and (3) A review and evaluation of Multi-Criteria Assessment techniques that might be applied to facilitate resource allocation across the diverse objectives of the USMC. We found that the ERM literature was not mature to the point of making strong recommendations for expensive implementations beyond the requirements of compliance. We thus recommended the simplest workable procedures we could find that would accomplish the goals of probability elicitation and multi-criteria portfolio analysis.

Keywords: *enterprise risk management, ERM, management fashion, probability elicitation, portfolio analysis, compliance*

Background

In 2016, OMB issued a revision to its Circular A-123 that added a mandate for federal agencies to implement ERM. The new provisions were accompanied by the addition of a recommendation in Circular A-11, which regulates the federal budget preparation and strategic planning process, and states that agencies should "leverage and incorporate" risk information from their ERM programs (U.S. Government Accountability Office [GAO], 2016, p. 2; OMB, 2020, Sections 31.8, 230.1 and 270). In this context, USMC is undertaking studies, including this one, to support more effective ERM implementation.

Findings and Conclusions

In the first task, a formal Systematic Narrative Meta-Analysis (SNMA) (McElroy, 2019) conducted in support of this project uncovered three meta-narrative themes related to successful ERM implementation and two meta-narrative themes associated with how ERM adds value to an organization. The themes uncovered support the quantitative work undertaken in the rest of this report. However, only four of the papers in a search that started with over 300 received the highest score on all quality-related factors (empirical content, critical evaluation, found useful by other researchers). Viewing this literature through the lens of Management Fashion (Abrahamson, 1996), we concluded that the public sector ERM literature is still in a growth phase, a phase in which most of the articles are merely promotional, and contain opinions not data.

The implications of findings related to the first research question are that USMC should proceed with caution in the implementation of ERM, to assure they receive incremental benefit from their investment in its implementation. While, certainly, the USMC must come into compliance with regulatory requirements related to ERM, the current state of knowledge about the incremental value the ERM initiative provides to strategic decision making does not necessarily justify a major expenditure on, for example, technology for data capture, or expensive consulting services, beyond what is required for compliance.

In pursuit of the second task, Farhar (2020) interfaced with USMC P&R during its Program Objective Memorandum (POM) development process, as it evolved its data collection procedure called McPrime from release 1.0 to release 2.0. We discovered that some of the commands working with P&R did not yet have a common language for risk, and that the 1.0 release (the only data P&R could make available to us) was not suitable for a risk analysis. We worked with the developers of McPrime 2.0 to modify their data collection so that risk analysis could be undertaken in the next POM cycle.

In pursuit of the second research question, we made several suggestions for better-capturing risk data with McPrime 2.0. Those recommendations revolved around the establishment of performance metrics for each MCPC, so that the impact of uncertainty on those metrics could be captured. As the primary "risk" POM preparation is budgetary, we made suggestions to capture the range of likely impact (e.g., a measurement of uncertainty) on performance metrics, given various levels of budget allocation. In particular, we recommended capturing worst case, best case and most likely performance impact for each funding level. These three-point estimates allow the fitting of a probability distribution so that risk analysis can be done during budget allocation. See Figure 1 for an example output using hypothetical data.

Our work on the third task included two literature reviews, the first assessing the basic Multi-Criteria Assessment (MCA) techniques used to rank alternatives that have incommensurable criteria, and the second (in Appendix Two) examining the evolution and current use of portfolio decision analysis in military applications. We found that many alternative MCA techniques existed, but that systematic comparisons between them were rare, and research that compared the techniques based on organizational performance prediction were almost non-existent (we found one paper). In other words, the literature had little empirical support for any claim about which techniques were most likely to help improve decision making.

For the third research question, in the absence of strong evidence favoring more sophisticated approaches, we recommended using the simplest procedures that have been found useful. We used data from McPrime 1.0, plausibly "extended" to incorporate uncertainty information and performance thresholds that are being captured in McPrime 2.0 to illustrate a portfolio approach based on Simple-Aggregate-Weighting (SAW), and an even simpler non-aggregating compensatory approach. See Table 1 for an example from the paper, allocating a budget cut to three Marine Corps Program Codes (MCPCs) based on hypothetical data. We demonstrated the issue with aggregating criteria scores, and how those aggregated scores are difficult to interpret, in terms of the mission objective – performance they are meant to reflect – and recommended the non-aggregating approach shown in Table 1.

Recommendations for Further Research

We recommend USMC Programs and Resources (P&R) continue to research ways to develop a common risk language across USMC, and a common understanding of risk analysis for the POM process. We further recommend USMC continue to evolve methods of probability elicitation, researching more advanced techniques based on their incremental value. Finally, we recommend USMC P&R research and develop ways to provide feedback to decision makers in order to improve the accuracy of probability assessments over time.

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Marine Corps Combat Development Command

NPS-19-M027-A: Evaluating/Improving Representation of Intelligence Capabilities and Processes in Combat Modeling with Demonstration in COMBATXXI

Researchers: Curtis Blais, Dr. Imre Balogh, Mr. Terry Norbraten, Mr. David Reeves, and Mr. Kirk Stork,
Student Participation: No students participated in this research project.

Project Summary

The 2016 United States Marine Corps (USMC) Operating Concept describes an enhanced concept of intelligence that enables the force to "establish and maintain battlespace awareness, influence the operating environment, and support decision-making at higher headquarters and on down to the point of action" (United States Marine Corps [USMC] 2016, p. 19). Simulating such capabilities requires representation, up and down the command hierarchy, of intelligence collection, processing, dissemination, and utilization as well as representation of battlefield effects resulting from the availability and application of such intelligence. Representation of these processes in combat simulations is critical in influencing combat outcomes, which provide an analytic basis for warfighting requirements and system acquisition decisions. As the USMC and US Army evolve capabilities and tactics, techniques, and procedures in the area of intelligence, models must be able to represent current intelligence capabilities as a baseline for studies, and must be modifiable to enable analysts to represent future capabilities for comparison.

This Naval Research Program (NRP) broad area study investigated and evaluated current capabilities implemented in the USMC/US Army Combined Arms Analysis Tool for the 21st Century (COMBATXXI), the primary analytic simulation used by both services to support studies of future warfighting systems, capabilities, and methodologies. While addressing broad intelligence processing modeling considerations, the project examined specific effects of intelligence modeling on scenario execution outcomes and recommended improvements to COMBATXXI capabilities.

The study team found there is no systematic representation of the intelligence process in COMBATXXI, and key functional components (e.g., data fusion) need improvement. Based on our analysis, the team recommended the following: a set of specific changes to the simulation logic, the need for follow-on work to create a coherent representation of the intelligence process in the simulation, and further investigation of interactions between the improved intelligence model and communications modeling in COMBATXXI.

Keywords: c*ombat modeling, intelligence process, behavior representation, Combined Arms Analysis Tool for the 21st Century, COMBATXXI*

Background
The 2016 Marine Corps Operating Concept describes an enhanced concept of intelligence as follows: "Current and future forces will increasingly rely on sensors, networks, architectures, and tradecraft to establish and maintain battlespace awareness, influence the operating environment, and support decision-making at higher headquarters and on down to the point of action. ... [We] must seek to capture the value of pushing networked intelligence down to tactical units throughout the MAGTF [Marine Air-Ground Task Force]" (USMC 2016, p. 19).

Simulating capabilities described in the operating concept requires representation of intelligence collection, processing, dissemination, and utilization up and down the command hierarchy, as well as representation of battlefield effects resulting from the availability and application of such intelligence. In combat simulations, these processes must influence combat outcomes that provide an analytic basis for warfighting requirements and system acquisition decisions. As the USMC and US Army evolve systems, tactics, techniques, and procedures in the area of intelligence, models and simulations must be able to represent current intelligence capabilities as a baseline for studies, and must be modifiable to enable analysts to represent future capabilities for comparison.

In recent years, the Naval Postgraduate School (NPS) Modeling, Virtual Environments, and Simulation Institute has developed tools and behaviors in the USMC/US Army COMBATXXI simulation to express ship-to-shore maneuver plans and execution, as well as fire mission plans and execution supporting USMC studies. These efforts took similar approaches in re-assigning assets as prior simulated mission assignments are completed, permitting the processes to proceed automatically throughout a scenario. For example, Harder (2017) prototyped an automated planner for maneuver and fire. Using advanced terrain reasoning, subsequent NPS students have added capability to Harder's framework for maneuver planning. Although these efforts provide a proof-of-principle for the proposed intelligence modeling approach, they generally have been limited to a single layer of the command hierarchy. Modeling intelligence planning, collection, processing, exploitation, and dissemination needs to exhibit the fractal property of self-similarity across all levels of the command hierarchy. That is, the representation of intelligence at each layer of the command hierarchy must consider characteristics that are found at each level, such as: (1) the layer of interest has direct authority over some set of intelligence assets; (2) the layer of interest may request intelligence assets from a higher authority; (3) the layer of interest can direct the use of intelligence assets under the command authority of a subordinate; and (4) the layer of interest may request intelligence assets under the command authority of some adjacent force. This conceptual similarity at each level of the command structure provides an effective starting point for designing generic system logic and behaviors that can be assigned to any level. In short, a model of the intelligence process needs to consider assets available, capabilities of those assets in space, time, and collection characteristics, as well as recognition of the kind of missions that need to be performed (from which information requirements can be derived).

Findings and Conclusions
The purpose of this NRP broad area study was to evaluate and improve the representation of intelligence in combat simulation, with demonstration of capabilities using the USMC and US Army COMBATXXI simulation. Since COMBATXXI is an important analytical tool for conducting studies, the USMC has interest in understanding its capabilities to support studies of different mixes of intelligence assets and processes on warfighting effectiveness.

To address the purpose of the study, the research team performed the following tasks:

1) Requirements Analysis: The study team obtained a current set of requirements from the Marine Corps sponsor and derived a set of software requirements for the intelligence model from a study of doctrine and tactics, techniques, and procedures applicable to the major elements of the intelligence process.
2) Conceptual Modeling: The study team developed a preliminary conceptual model of the intelligence process to identify principal objects and interactions that need to be represented to address the intended use and derived requirements. This portion of the project identified algorithms and data needed to represent capabilities and processes in the simulation.
3) Simulation Design: The study team identified new capabilities needed in the target implementation environment (COMBATXXI), including improvements to capabilities that may be present currently in the simulation.
4) Simulation Implementation: The study team implemented selected aspects of the identified design to demonstrate potential opportunities for supporting studies of intelligence capabilities in the Marine Corps.
5) Recommendations: The study team recommended future actions to improve the modeling capabilities of simulations such as COMBATXXI.

While addressing the broad modeling considerations, the study team investigated and evaluated current capabilities implemented in the COMBATXXI. The team conducted experiments with the current implementation to examine simulation outcomes and to recommend improvements to COMBATXXI capabilities. Although COMBATXXI provides several functional capabilities relating to particular aspects of intelligence planning, collection, processing, and dissemination, the study team found that it has no comprehensive approach that can support such studies. The study outlined a methodology for planning and employing sensor assets to provide information needed by simulated warfighters at various levels of command in the situation under study. The study identified current shortfalls for improvement and described a full model of the intelligence process for consideration in future development projects.

Recommendations for Further Research

The study recommended that the Marine Corps continue research and development to address key requirements stated in the 2016 Marine Corps Operating Concept; specifically, the study team considered the following areas from the operating concept to be ready for immediate follow-on work to this Naval Research Program study. First, enhanced simulation can explore data strategies and information sharing architectures to achieve benefits from machine-aided tipping, machine-aided relational visualization and display of battlefield threats, and opportunities that help commanders and other decision makers quickly and intuitively understand complex situations. Second, simulation can examine use of unmanned intelligence, surveillance, and reconnaissance systems that can provide actionable in ways that support distributed units with highly compressed timelines for situation awareness, intelligence, decision-making, and action. Third, simulation can investigate the inherent opportunities in viewing every aircraft and every vehicle, potentially even every individual Marine, as a battlefield sensor. Fourth, simulation can examine effects of task-organizing Marine Air-Ground Task Forces (MAGTFs) to include mission-appropriate intelligence capabilities through a consistent approach to develop Marines qualified to staff mutually supporting intelligence nodes across all MAGTF organizations, and developing a tailorable common operating picture that can be distributed based on mission and user needs (USMC 2016, p. 19). Preliminary steps toward such capabilities were demonstrated as part of this study.

Specific recommendations for improvement of the Combined Arms Analysis Tool for the 21st Century (COMBATXXI) included: design and implementation of identified improvements to the COMBATXXI data fusion logic, and design and development of complete behaviors representing the intelligence process (planning and direction, collection, processing and exploitation, analysis and production, dissemination and integration, evaluation and feedback) at all levels of the command hierarchy.

Each of these operating concepts can be represented in models and simulations, such as COMBATXXI, to provide a foundation for evaluation of alternative systems, tactics, techniques, and procedures. Without such rigor, it will be difficult to impossible to understand the complex interrelationships found in the various combinations of collection assets, organization, information flows, and data structures, all in the presence of a determined enemy intent on disrupting warfighter performance. Of course, such representations also serve as a basis for modeling enemy processes that US forces seek to disrupt in kind.

Lastly, there is an interesting interplay of the overall intelligence process with other areas of investigation in combat modeling for Marine Corps studies, namely, modeling communications and modeling human physiology and psychology. Intelligence collection and dissemination rely on communications capabilities that can be degraded, denied, or distorted by enemy actions or characteristics of the physical battlespace. The ability to interpret and analyze collected information and perform effective decision-making, when these activities are not fully automated, depend on the physical and cognitive condition of the human decision makers (Shattuck et al., 2007). Given these factors, the study team also recommended continuing research to model the complex interplay of intelligence, communications, and human physiology/psychology to create greater opportunities for studying key factors in the modern battlespace that lead to success or failure of combat operations.

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NPS-20-M046-A: Tactical Cybersecurity Decision Matrix for COTS UAS

Researchers: Dr. Douglas Van Bossuyt and Dr. Britta Hale
Student Participation: Aaron Daponte CIV, Gregory Maguire CIV, and Calvin Roldan CIV

Project Summary
The Department of Defense (DOD) lacks a suitable method for identifying and managing the cybersecurity risks associated with commercial off-the-shelf (COTS) unmanned aerial system (UAS) use. With no methods to mitigate the cybersecurity risk, in a memorandum by the deputy secretary of defense on May 23, 2018, the DOD suspended the purchasing and use of COTS UASs until known cybersecurity risks and vulnerabilities could be mitigated. While exemptions to the directive are made on a case-by-case basis, this requires commands to submit a waiver before being able to utilize COTS UASs.
This research establishes a method to identify and mitigate the cybersecurity risk of COTS UASs at the tactical level: a cybersecurity risk-management decision matrix that would help produce a risk assessment to help tactical operators make informed operational decisions. More specifically, an architecture, method, and processes were developed for commands to create their own risk matrices. Utilizing a systems engineering approach, the UAS was broken down into subsystems to help identify potential cybersecurity vulnerabilities. These vulnerabilities were then used to create inputs to the matrix that would assign an output risk that tactical operators could use to make real-time decisions. The matrix was then validated using the National Institute of Science and Technology (NIST) framework.

Keywords: *cybersecurity, decision matrix, unmanned aerial system*

Background
Over the years, the United States military has used COTS UASs to support its missions in an inexpensive and effective manner. However, due to the cybersecurity vulnerabilities in COTS UASs and no method in place to mitigate the cybersecurity risks, the DOD suspended the purchasing and use of COTS UASs until a strategy was developed to mitigate said risks. This research works to provide a method for tactical operators to identify and mitigate cybersecurity risks of COTS UASs. The method of choice to achieve these results is through the creation of a cybersecurity risk management decision matrix.

Since different vulnerabilities and the effectiveness of certain protocols and their level of security change over time, a framework for developing a matrix is far more valuable than developing a solution that may become dated within a few years. By defining the process behind the creation of the matrix and demonstrating how operators would define inputs, assigning risk ratings, and developing the risk outputs, commands will be better equipped to handle the changing problem space for years to come. The intent is to help commands create their own cybersecurity risk management decision matrices for tactical operator use in making real-time decisions using the operational environment and other factors as inputs to the matrix.

Our objectives are as follows: identify and analyze potential RF, IP, and other operational COTS UAS risks, develop a methodology, process, and architecture for a cybersecurity risk management decision matrix which can be used in the use and approval of COTS UAS in the military at the tactical level, and verify the cybersecurity risk management decision matrix using NIST cybersecurity framework and DOD guidance, and/or other methods.

Findings and Conclusions

The systems engineering process used in the creation of the cybersecurity risk management decision matrix consisted of multiple, iterative phases to meet stakeholder requirements. These phases included identifying the need, researching the need, developing possible solutions, selecting the best solution, constructing a prototype, testing and evaluating, communicating the solution, and reevaluating. Additionally, the testing and evaluation phase functions to ensure the developed matrix meets the stakeholders needs, by using the NIST cybersecurity framework. Any gaps between the NIST cybersecurity framework and the proposed matrix identifies faults in the system design, which were then corrected and re-evaluated using the NIST cybersecurity framework.

Once stakeholder needs were identified, a functional analysis was conducted to better understand how the project team could create the cybersecurity risk management decision matrix. This was accomplished by examining the common COTS UAS in smaller functional entities. During the functional analysis, four subsystems were identified, including: the ground control station, the unmanned aerial vehicle, the up/down control link, and other external factors, such as the location of the operational area. With these four subsystems defined, potential cybersecurity vulnerabilities were identified in each functional piece of the UAS. This research analyzed different protocols used by COTS UASs, thereby identifying potential cybersecurity vulnerabilities. Therefore, we focused on those commonly used in COTS UASs, as well as the COTS UAS vulnerabilities: command and control links, Wi-Fi, and GPS links. As each have a variety of different modes and protocols, they were individually researched to allow assigning of a cybersecurity risk code. These cybersecurity vulnerabilities were then used to create inputs to the cybersecurity risk management decision matrix, which aided in assigning an output risk that tactical operators could use to make real-time decisions. Using the three main inputs, cyber-attacks, cyber vulnerabilities, and operational environment, a set of three outputs to the matrix were derived, intended to direct the operators' decisions. These outputs are as follows: Most Likely Cyber Attacks, Symptoms and Risk Rating.

Once the matrix architecture was established, a sample cybersecurity risk management decision matrix was created to demonstrate how commands could create their own matrices using the proposed architecture. Based on the widespread availability of Excel and a lower potential of human error by tactical operators using other methods, it was decided to implement the cybersecurity risk management decision matrix in Microsoft Excel VBA. In short, the proposed methodology for the construction of a cybersecurity risk management decision matrix effectively satisfies stakeholder needs and the project objectives, including developing a cybersecurity risk management decision matrix architecture and methodology, identifying COTS UAS risks to use as inputs to the matrix, and validating the matrix architecture using the NIST cybersecurity framework.

Recommendations for Further Research

While conducting research and development of the cybersecurity risk management decision matrix architecture, several potential needs were identified. These needs could spur future research in other, more specific areas of study regarding the cybersecurity risk management decision matrix for commercial-off-the-shelf (COTS) unmanned aerial systems (UASs). The first area of consideration is performing a real-world validation exercise with tactical operators to identify any shortcomings of the matrix architecture design. This would also allow the tactical operators to tailor the matrix to their own cybersecurity risk assessment needs, providing an opportunity to see how easily this can be implemented on a larger scale. Another consideration for future work is to study the best method for implementing the cybersecurity risk management decision matrix. Since the matrix architecture is developed using Excel, future work would need to be done to see what other platforms could support this matrix, including putting the matrix on a web or phone-based application. The third consideration for future work is the development of an expansion library of other protocols and vulnerabilities. While this study focuses heavily on radio frequencies, global positioning systems (GPS), and Wi-Fi vulnerabilities, there are many other protocols in existence, and the list will continue to grow as new technology emerges. For instance, although not too common, there are currently UAS utilizing 5G cellular networks instead of Wi-Fi to connect the aerial vehicle to the operator. The final consideration for future works is to apply a time-phased use of the matrix. The time-phased cycle would start during the acquisition phases, and continue through the pre-mission, during mission, and post mission phases. Since there are different operational risks at each phase, there are additional inputs to the matrix that could be considered.

NPS-20-M124-A: Evaluating and Improving the Representation of Degraded Communications in the USMC/Army Combined Arms Analysis Tool for the 21st Century (COMBATXXI)

Researchers: Dr. Curtis Blais, Dr. Imre Balogh, Mr. Terry Norbraten, CAPT Kirk Stork USN Ret., and Mr. David Reeves
Student Participation: No students participated in this research project.

Project Summary
The Combined Arms Analysis Tool for the 21st Century (COMBATXXI) is one of the principal simulation tools used by Marine Corps analysts to support studies of future warfighting systems and capabilities. COMBATXXI was developed jointly by the US Marine Corps Operations Analysis Directorate Combat Development and Integration (OAD, CD&I) and the US Army Futures Command 'The Research and Analysis Center', White Sands Missile Range. Based on known and suspected threats to its tactical networks, Marine Corps analysts anticipate increasing importance in evaluating these threats in future studies. Simulations such as COMBATXXI must be able to represent combat capabilities in light of these threats. In discussions with OAD CD&I representatives, it was agreed that the current state of the COMBATXXI communications model needs to be understood before the larger question of the effects of degraded communications on combat can be examined. Therefore, the purpose of this Naval Research Program broad area topic was to examine current capabilities of the COMBATXXI communications model to identify areas for improvement. To do so, the study team identified Marine Corps study requirements related to tactical communications and degraded communications, examined existing COMBATXXI capabilities to represent and meet those requirements, identified gaps between required capabilities and existing capabilities, and recommended improvements to COMBATXXI to address the gaps. The study team found that there are significant capabilities in COMBATXXI to support the studies of interest, although there has been limited use of the functionality due to a lack of specific studies requiring those capabilities. The study team recommended that CD&I identify an analysis objective that can be addressed by developing one or more relevant scenarios to more fully exercise COMBATXXI's representation of communications and factors influencing communications

performance. This would also prompt the development of entity and unit dynamic behaviors under varying natural and hostile conditions.

Keywords: *tactical communications, communications modeling, combat simulation, jamming; environmental effects, degraded communications, Combined Arms Analysis Tool for the 21st Century;* COMBATXXI

Background

In today's modern battlefield, tactical communications and networking are essential to overall command, control, and coordination of forces. Knowing our reliance on such technologies, hostile forces seek to disrupt, and even deny, the use of such capabilities to degrade the ability of forces to conduct warfare effectively. The Army and Marine Corps co-developed the COMBATXXI simulation to support various warfighting analyses, and put significant development effort into modeling of communications at different levels of resolution. However, to date, these models have not been used in specific studies and, consequently, the implemented logic has not been thoroughly exercised. In the meantime, as introduced above, warfighting capabilities have evolved to become highly dependent on reliable communications and digital networking. Marine Corps analysts anticipate that future studies will require use of COMBATXXI communications models and possibly new models representing emerging operational concepts. Therefore, Marine Corps analysts need to be assured that communications capabilities are effectively represented in COMBATXXI software or, as needed, that deficient areas are identified for development or modification. As a starting point, the Marine Corps required a thorough review and assessment of current COMBATXXI software to establish an understanding of current functional capabilities implemented in the product.

Findings and Conclusions

Our research focused on determining the capabilities of COMBATXXI in simulating tactical communications and networking at a sufficient level of resolution and fidelity to meet Marine Corps analytical study requirements. Because this area of the COMBATXXI simulation has not been exercised significantly, the sponsor and the Naval Postgraduate School study team hypothesized that the current implementation may no longer be operating correctly, if at all.

To perform this research, the study team met with the topic sponsor to re-established Marine Corps requirements for communications modeling in COMBATXXI. The team conducted a detailed review of existing COMBATXXI software documentation, data, and code with respect to communications modeling. Part of this effort involved executing example scenarios in COMBATXXI to verify if the software produced expected results in accordance with code implementation and software documentation. Analysis of current capabilities resulted in identification of gaps between requirements and capabilities, leading to a set of recommended improvements to COMBATXXI. Through this process, the study team identified modeling approaches and capabilities that can inform design of other combat simulations, even those used for other purposes, including training, or test and evaluation.

Overall, we found that COMBATXXI has significant capabilities to represent communications networking and possible degradation, such as jamming, due to environment and hostile action. Since past studies have not required the use of this functionality, there are few entity and unit behaviors for determining actions to take when hostile or natural causes disrupt, degrade, or corrupt communications. Moreover, the military community has a growing interest in how cyber-warfare will affect combat performance. While COMBATXXI developers have demonstrated some potential capabilities in this area, it remains open for future development and study.

Recommendations for Further Research

Based on our study, determining additional capabilities needed in the Combined Arms Analysis Tool for the 21st Century (COMBATXXI) depends on the level of detail and breadth of functionality needed to conduct specific analyses of interest to the Marine Corps. To advance capabilities in the software, we recommend that the Marine Corps analysts should identify specific study requirements, and representative scenarios, to more fully exercise COMBATXXI functionality in its representation of communications and factors influencing communications performance. Such scenarios would also prompt the development of entity and unit dynamic behaviors under varying conditions of natural and hostile degradation of communications performance. While this work focused on the COMBATXXI simulation, project findings can be applied to modeling efforts in other Marine Corps communities, such as training and experimentation.

NPS-20-M129-A: Improving Physiological Modeling in Combat Simulations

Researchers: Dr. Curtis Blais and Dr. Imre Balogh
Student Participation: No students participated in this research project.

Project Summary

The United States military has entered an era where unmanned and autonomous systems are expected to play an increasing role in delivering greater warfighting performance. While expectations are high, the analytical community does not possess the simulation tools and techniques to quantitatively represent and assess the performance of various mixes of manned and unmanned systems. Specifically, simulations used in acquisition studies must differentiate performance between humans and machines, when operating separately and in teams. Earlier research has shown that the primary capability lacking in analytical simulations today is a realistic representation of the capabilities of humans in the battlespace; we first require improvement in the modeling of human systems. To this end, the United States Marine Corps (USMC) has a need for high-resolution models of physiological effects on task performance to explore the trade space across mobility, survivability, and lethality. The objective of this Naval Research Program thesis topic was an analysis of state-of-the-art modeling of human performance in combat simulations. The study focused on physiological considerations of endurance, energy, and maneuver speed/agility, with potential effects on perception, information processing, and decision-making.

Unfortunately, the study team was unable to recruit students to perform this research, so we performed a literature review to establish a foundation for follow-on work. The existing Combined Arms Analysis Tool for the 21st Century (COMBATXXI), jointly developed by the USMC and the US Army to support studies of future warfighting systems and capabilities, was used as an example simulation for examining current capabilities in modeling human physiology, and its effects on combat and for evaluating physiological models of interest. The analysis resulted in recommendations of improvements to

COMBATXXI capabilities to improve representation of human performance and its effects on warfighting, while providing information that can be applied to other combat simulations.

Keywords: *combat simulation, human performance modeling, human physiology modeling, human psychology modeling, Combined Arms Analysis Tool for the 21st Century, COMBATXXI*

Background

Historically, combat simulations have represented humans very much like robots, exhibiting few, if any, of the physiological and psychological factors that can affect human performance and the outcome of combat. Moreover, the differences between individual humans are not normally represented explicitly, but they are considered to some degree in data; i.e., United States Marine Corps (USMC) simulations often represent the "average Marine." In the real world, unit performance in combat may be more dependent on variability in performance across a collection of Marines (or in the context of other forces/organizations). The US military has entered an era where unmanned and autonomous systems are expected to play an increasing role in delivering greater warfighting performance. While expectations are high, the analytical community does not possess the simulation tools and techniques to quantitatively represent and assess the performance of various mixes of manned and unmanned systems (Blais & McGregor, 2016). Students at the Naval Postgraduate School have addressed research questions relating to the effects of load and individual body type on dismounted mobility (Sasala, 2018). Likewise, researchers at the RAND Corporation have defined a "will to fight" model that depends on numerous psycho-social factors, including cultural and social influences, at various levels of the military organization (Connable et al., 2018). Although these are valuable results, it is not yet clear how physiological models can be integrated with the psycho-social models to obtain more complete and realistic representations of human performance in combat. Examples of modeling approaches exist, but little has been done in a systematic way to incorporate such models into combat simulations, and even less has been done to distinguish human system performance from unmanned system performance in a meaningful way.

Findings and Conclusions

Our research investigated current and emerging models of human physiology in combat in order to identify the following: primary aspects of human physiology that influence human performance in combat; existing mathematical models or simulations that represent the identified aspects of human physiology influencing human performance in combat; capabilities of existing analytical simulation(s) used by the Marine Corps to represent aspects of human physiology influencing human performance in combat; how improved capabilities can be incorporated into existing analytical simulation(s) of interest to the USMC; and recommended improvements to existing USMC analytical simulations to provide a roadmap for future model development.

While our primary focus was on human physiology in combat, the study's scope was expanded to include a preliminary consideration of human psychology and human cognition in combat. This decision reflected the close interrelationships between physiology and psychology (e.g., effects of stress and fatigue on cognition). The study team considered models from the perspective of possible integration into the COMBATXXI simulation, which is the principal analytical simulation used by the USMC and US Army for studies informing high-level acquisition decision-making. Although focused on COMBATXXI as a principal model used by the Marine Corps, the identification of important modeling considerations is applicable to a wide range of applications, including the training, experimentation, and test and evaluation domains. All these domains need improved representation of human performance, especially as the military continues to develop and deploy unmanned systems requiring an ability to distinguish between human performance and unmanned system performance.

Given a lack of student participants, the study team was not able to perform as detailed a study as would have been possible otherwise. Despite this, the team examined literature relating to various aspects of the problem, with emphasis on source materials for the RAND "Will to Fight" model (Connable et al., 2018). The team examined several existing and emerging combat models and simulations to determine how principal aspects of human physiology were addressed, and if the models would be suitable for incorporation into a simulation such as COMBATXXI. Given the identification of key physiological considerations to include in combat models, plus knowledge gained about how such considerations have been modeled previously (mathematically or in simulation) and current capabilities available in COMBATXXI, the team identified several recommendations on capabilities that can be added to COMBATXXI (or any other simulation) to better represent the effects of physiology on combat outcomes.

Recommendations for Further Research

Our results include a literature review of references influencing several current modeling efforts, which provides a foundation for future student or faculty research. We also considered current capabilities of simulation systems such as the USMC/US Army Combined Arms Analysis Tool for the 21st Century (COMBATXXI). From the information reviewed and analyzed in this research, the study team recommended that the USMC should continue to encourage student and faculty research to identify and incorporate models of human physiology in COMBATXXI by initiating studies to identify and incorporate models of human psychology, cognition, and decision-making in COMBATXXI. Further, the USMC should initiate development and analysis efforts to represent and study the complex interaction of human physiology and psychology with intelligence and communications processes in COMBATXXI, while also representing mixes of human systems and unmanned/autonomous systems in COMBATXXI. These recommended efforts will enable the USMC to represent future warfighting scenarios involving the interplay of human systems and unmanned systems, together with the physical and psychological factors influencing future warfighting.

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NPS-20-M183-A: MCWL Innovative Employment of the F35B in Contested Environments

Researchers: CAPT Jeffrey Kline USN Ret., Dr. Jeffrey Appleget COL USA Ret., and Dr. Robert Burks COL USA Ret.
Student Participation: Maj Robert Jankowski USMC, Capt John Howser USMC, Maj Steven Kasdan USMC, LT Eric Myers USN, MAJ Nicholas Lazzarevich USA, Capt Jeremy Barton USMC, and LTC Joshua Perry USAR

Project Summary
The Expeditionary Advanced Base Operations (EABO) concept calls for the use of land-based anti-ship missiles (ASM) in support of Fleet Sea Denial operations. These bases will persist within the first island chain and must remain small and mobile in order to survive. This project's original intention was to explore employment of the F35B to augment EABO surveillance and offensive operations; however, due to classification restrictions on data and COVID19 constraints on face-to-face wargaming, the sponsor redirected activities to address command and control, surveillance systems, and missile alternatives. In a three-step series of warfare analyses, this research advanced the Marine Corps Warfighting Lab's (MCWL) concept development for EABO, specifically focusing on command and control and land-based, anti-ship alternatives to enhance sea denial capabilities. A campaign analysis was conducted to compare mobile anti-ship missiles, surveillance, and targeting systems with different command and control structures, followed by designing, developing, and executing a wargame to compare centralized with decentralized EABO command. Insights from both efforts were then used to conduct advanced experimental design and agent-based simulation to refine recommendations to the Marine Corps Warfighting Lab.

Although specific findings are restricted information, they included quantifying the advantages of decentralized command over a rigid centralized alternative, the advantages and limitations of the use of weapon engagement zones specific to EABO geographic locations, analysis of alternatives between anti-missile types and their ranges, and current limitations of surveillance and targeting assets. Emerging technologies like the medium displacement unmanned surface vehicle (MDUSV), the Hermes 900 Medium Altitude Long Endurance (MALE) Maritime Reconnaissance unmanned aerial vehicle, and the Sierra Nevada Corporation Solar Powered Balloon were compared in various surveillance and targeting force structures to provide best battle space awareness and targeting coverage.

Keywords: *expeditionary advanced base operations, EABO, land based anti-ship missile, ASM, command and control, medium displacement unmanned surface vessel, MDUSV, medium altitude long endurance, MALE*

Background
Naval operations conducted under potential adversaries' area denial weapon ranges are high risk to friendly forces operating in open oceans. In response, the MCWL is developing the concept of EABO to enable distributed land-based offensive operations to threaten adversary sea operations under the adversary's threat umbrella. Questions on how best to equip Marines with anti-ship missiles, which surveillance and targeting systems to employ, and what resilient command and control methods to

operate under are subject to these concept exploration efforts.

Findings and Conclusions

A four-officer team from the Winter Joint Campaign Analysis Class analyzed alternative missile and surveillance systems along with various command and control methods to provide recommendations on missile types and new technologies to consider for acquisition to support sea denial operations (Jankowski, Howser, Kasdan, and Meyers, 2020). Geo-analysis, simulation, and combat modeling was used by the team to conduct their study. Two major findings came from that effort. The first was the need to ensure surveillance and targeting ranges match missile ranges. To this end, the Marine Corps needs to acquire longer range locally employed surveillance capabilities, like the MDUSV and the Hermes 900 MALE maritime reconnaissance unmanned aerial vehicle. The second finding quantified the advantage of decentralized command and control and intelligent use of weapon engagement zones between EABOs.

In the following academic quarter's Wargaming course, several members from the Joint Campaign Analysis effort designed, developed, and executed an analytical wargame specifically focusing on comparing the advantages and disadvantages of centralized and decentralized command and control. The team worked directly with the MCWL sponsor to define the game's objective for data collection. The game's final analytical report detailed the advantages of decentralized command and control for EABO operations, while demonstrating methods for cross-coordination in Weapon Engagement Zones (Jankowski, Lazzarevich, Perry, Barton, and Howser, 2020).

Finally, Captain John A. Howser, USMC, who was involved in both the Joint Campaign Analysis study and the wargaming effort, conducted intelligent experiment design and simulation to advance insights in anti-ship missile requirements for his Operations Research Master's Degree thesis (Howser, 2020). Captain Howser simulated thousands of tactical engagements to obtain sufficient data to allow parametric exploration into the most important factors associated with land-based, anti-ship missile capabilities. Specific results are restricted information, but his quantitative assessment paralleled findings from the campaign analysis and wargaming efforts.

All research projects including the Joint Campaign Analysis briefing, papers, and team summary, wargaming report, and Captain Howser's thesis were provided to MCWL staff.

Recommendations for Further Research

Specific recommendations are restricted and were provided to Marine Corps Warfighting Laboratory staff; however, they include further analysis to inform the Marine Corps on alternatives to provide longer range locally employed surveillance systems to match anti-ship missile ranges. In addition, further analysis is needed to develop tactical doctrine for Expeditionary Advanced Based Operations' decentralized command and control and use of weapon engagement zones.

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Marine Corps Systems Command (MARCORSYSCOM)

NPS-20-M041-B: Supply & Maintenance Predictive Modeling and Simulation Analysis Tool

Researcher: Dr. Ying Zhao
Student Participation: No students participated in this research project.

Project Summary

Marines in combat require a rapid and flexible logistics capability responsive to the 21st century battlefield. The USMC's supply and maintenance chain receives data feed from a long chain, including maintenance, requisition, transportation, and finance processes, activities, and decisions. Such a complex enterprise needs trusted deep analytics, including machine learning (ML) and artificial intelligence (AI) methods to achieve automation, improve readiness, and win in unexpected environment. In this project, we first review an overall framework of leveraging artificial Intelligence to learn, optimize, and wargame (LAILOW) for a complex enterprise, and then show how the LAILOW framework is applied to the USMC supply and maintenance chain as a test case. We have applied a collection of supervised machine-learning algorithms from an open-source tool Orange (based on the python ML library scikit-learn) to predict business metrics such as predict probability of fail (POF). We then show an unsupervised machine learning method lexical link analysis (LLA) to discover associative and sequential patterns, combined with predictive models in a game-theoretic set up of the LAILOW framework, where demand perturbations introduced by high-impact and low-occurrence items propagate to the whole system. We have showed the LAILOW framework as predictive and simulation tool using data sets extracted from operational databases to improve total readiness, agility, and resilience for the USMC logistics enterprise. We delivered two publications from this project, and one has been accepted in an IEEE/ACM conference (Zhao & Mata, 2020), and other one is out on submission (Zhao et al., 2021).

Keywords: *supply and maintenance chain, predictive modeling, simulation analysis tool machine learning, ML, artificial intelligence, AI, game theory, wargame, genetic algorithms, coevolutionary algorithms, reinforcement learning, GCSS-MC*

Background

Deep data analytics including ML algorithms have been used by the USMC to address variety of challenges and support the Marine air-ground task force (MAGTF) operations (Mata 2019a; 2019b). Predictive methods of supervised ML have been used to predict equipment reliability and POF, therefore infer numbers of spare parts to improve stock performance, synchronize budget execution, and decrease maintenance cycle time. Stocking parts based on the ML predictive maintenance models helps prevent ordering surplus or unnecessary components for “just in case” or better known as the Iron Mountain Concept.

Optimization methods are also needed for optimizing diversity of distribution. Distribution systems need to maximize throughput capacity for a Physical Network Analysis or Logistical Network Analysis (LNA) at nodes and arcs, to determine the most reliable LNAs, to predict the rate of flow of the LNAs, to deliver widgets from the warehouse, and to fighting hole most expediently and efficiently to match the combat power necessary. Thus, planners would be able to forecast better the rate of combat power entering into an area of operation to avoid congestion or delays.

The hypothesis for this work is that the USMC can adopt advanced data sciences including ML/AI and game theory techniques to address the specific operational requirements in a short-term; enhance the total force readiness to project combat power across a wide range, spectrum of military operations in a long-term. Our objective is to apply innovative ML, optimization, and game theory algorithms. Specifically, we have applied Soar reinforcement learning (Soar-RL) integrated with the coevolutionary algorithms to leverage AI to LAILOW. In our previous work, Soar, a cognitive architecture (Laird, 2012), and reinforcement learning (Sutton, 2014), a class of ML/AI algorithms capable of automating cognitive functions of warfighters, were shown from the tactical decision-making (Zhao, 2016; Mooren, 2017; Zhao et al., 2017, 2018).

Coevolutionary algorithms (Popovici et al. 2012, pp. 987-1033; O’Reilly & Hemberg, 2018), related to genetic algorithms (Back, 1996; Goldberg, 1989), explore domains in which the quality of a candidate solution is determined by its ability to successfully pass some set of tests. For example, solutions in a supply and maintenance chain need to pass known difficult environmental or adversarial tests. Coevolutionary algorithms are used to solve minmax-problems like those encountered by generative adversarial networks (Goodfellow et al., 2014; Arora et al., 2017). Coevolutionary algorithms take a population-based approach and can explore a different behavioral space and allow tests and solutions both adapt and evolve while pursuing conflicting objectives.

The combined framework, or LAILOW has been successfully used the data sets in this project to address the challenges. We delivered a demonstration and two publications from this project, and one has been accepted for an IEEE/ACM conference (Zhao & Mata, 2020), and the other is in the submission process (Zhao et al., 2021).

Findings and Conclusions

<u>Methodology</u> - The LAILOW framework can be summarized as follows:

Step 1 - Learn: recognizes patterns and rules from historical data. Patterns and rules describe the prediction, association and/or sequential patterns. For example, A USMC's unit structure includes equipment and parts to support the core equipment. Each core equipment and parts have specific need for the (X) duration and frequency of manpower and equipment for maintenance. One needs to first learn patterns for the causes of high cost or slow processing areas, and then use the pattern to predict the desired effects for the future data. We used an open-source tool Orange (2020) including typical predictive models such as logistic regression, decision trees, naïve Bayes, random forest, k-nearest neighbors, support vector machines, and neural networks among others. Soar-RL was also used as a predictive model compared to Orange. Specifically, for a maintenance service ticket, we predict the probability of the days between opened and closed date to be more than 65 days based on other attributes (Zhao & Mata, 2020). A unique unsupervised machine learning method, LLA, is used to discover association and/or sequential patterns that improve the prediction (Zhao & Mata, 2020).

Step 2 – Optimize: Based on the predictive patterns and association patterns developed from Step 1, LAILOW optimizes the measures of effectiveness or the measures of performances (MOPs), defined by business decision makers, by searching through better possible courses of actions for future requirements. A MOP, the probability of the days between opened and closed date being more than 65 days, is minimized.

Step 3 – Wargame: LAILOW represents a complex enterprise with a logistician/planner as a self-player in a game environment in real-time, and suggests winning actions, i.e., what supply and maintenance decisions can be the best solution for a service ticket (test).

Data Set and Process - To show the feasibility of this work, we have sampled data for a specific Table of Authorized Material Control Number (TAMCN, 2020) from the database Global Combat Support System-Marine Corps (GCSS-MC), including service ticket number level attributes related to maintenance data, supply data, and equipment usage data. The sample data set contains 2065 service numbers/tickets, where 599 (29%) have more than 65 days (65 days is the mean value of the days between the open and close dates for the data set), between their opened and closed date, which is the target variable for prediction.

Findings and Conclusion - We found Soar-RL results comparable in predictive accuracy for predicting the MOP. Since Soar-RL is also rule-based and explainable, it was selected and used in a simulation phase integrated with the coevolutionary algorithms. The simulation shows that the logistics solutions, on average, worsens in evolution (in terms of the MOP value), while the opponent, representing logistics tests, on average, improves in evolution in terms of the MOP. The algorithms systematically simulate and discover possible new tests or "vulnerability", and evolved solutions or "resiliency" are also discovered. Therefore, the LAILOW framework provides a holistic predictive and simulation platform to improve total readiness of a resilient and agile USMC logistics enterprise.

Recommendations for Further Research

Two recommendations for future research are as follows: It is imperative for United States Marine Corps (USMC) to adopt more advanced data sciences including machine learning/artificial intelligence (ML/AI) techniques to focus on the entire spectrum or end-to-end (E2E) logistic planning for the complex enterprise of maintenance, supply, transportation, health services, general engineering, manpower, lesson learned, and finance. Continuous work in this area jointly with the development of Global Combat Support System-Marine Corps (GCSS-MC) is necessary. The goal is to enhance the total force readiness and project combat power across the whole range of military operations and spectrum of conflict at any time. Leveraging AI to learn, optimize, and win game (LAILOW) framework, especially when equipped with lexical link analysis, Soar reinforcement learning, and coevolutionary algorithms, needs further research and testing as a prediction, optimization, and simulation platform. Eventually it can learn, search and discover new configurations, emerging properties, measures, and countermeasures for the Global Combat Support System-Marine Corps (USMC E2E) logistic planning modernization.

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NPS-20-M267-A: Maker Space Collaboration: Sharing Best Practices and Lessons Learned for Facilities, Equipment and Personnel

Researchers: Dr. Ibrahim Gunduz, and Dr. Amela Sadagic
Student Participation: No students participated in this research project.

Project Summary

Innovation labs and maker spaces will have a significant impact on future Navy and Marine operations. These spaces can be important catalysts for learning, collaborating, and experimenting with rapid prototyping and additive manufacturing (AM) and can accelerate the adoption of new technologies. The Naval Postgraduate School (NPS) RoboDojo is one example of an innovation space designed to promote hands-on learning to help the NPS community practice rapid prototyping using 3D printers, laser cutters, and other capabilities.

As part of this project, the investigators interacted with the United States Marine Corps (USMC) to design and produce an array of training materials to enable the start-up and enhancement of these spaces within USMC. These modules include the technical aspects of AM and AM best practices for adoption and group (team) innovation, introduction to 3D modeling with Fusion 360, raspberry PI and Arduino, custom computer builds, and lithium-ion polymer battery usage and storage.

Keywords: *maker space, innovation, collaboration, adoption, additive manufacturing, AM*

Background

More organizations are opening innovation labs solely dedicated to creating new solutions to challenges by empowering their members. The Department of Navy (DoN) aims to attain its goals of high operational readiness and enhanced force projection with significant cost savings by promoting its members' personal initiatives to rapidly translate into innovative approaches and agile response. The potential impact of a variety of novel and often low-cost technologies, including 3D printers, in the military domain is well recognized; however, these technologies have not been fully integrated into the DoN, specifically into USMC practices and processes. Repeated site visits and surveys by NPS faculty have shown that innovation-related capabilities are widely encouraged, sometimes supported, but rarely achieved in the long term. The threshold to engage with these technologies has come down significantly, allowing service members with little technical background to engage in often startling feats of technical prowess.

The adoption of novel ideas, physical artifacts, or processes is not a new research topic and it has been a subject of study for quite a long time. The most known modern theory is "diffusion of innovations," established by E. M. Rogers and his team (Rogers, 1995); the first edition of this seminal work was published in 1962. The specifics of different domains, like technology, were brought in by other authors to enrich the initial diffusion of innovations model. Modified models included user acceptance processes, for example the Technology Acceptance Model (TAM) introduced by Davis (Davis, 1986, 1989, 1993); details of perceived usefulness, such as the TAM2 model developed by Venkatesh and Davis, 2000; and intention and usage, notably the unified theory of acceptance and use of technology or UTAUT, introduced by Venkatesh et al., 2003. Multiple mechanisms were also found to enable and expedite diffusion of innovation and adoption of technology in any social group (Rogers, 1995; Davis, 1989; Venkatesh et al., 2000; Sadagic, et al., 2015). A common denominator for many adoption models is that they identify users' attitudes towards innovations as a key ingredient that influences the adoption process. Therefore, adopters' attitudes and opinions (both correct and incorrect from an objective standpoint) are confirmed to have a considerable impact on the adoption process.

When we study technology adoption, the large-scale adoption of technological innovation is of particular interest. The reason is straightforward—large-scale adoption provides an opportunity for a paradigm shift and change of how the group or institution operates in a given domain (Sadagic, 2008). That type of change also brings potential and a promise of being more productive in one’s task, supported by that technological innovation.

This research provides guidance on approaches and infrastructure that could be used to accelerate the creation and enhancement of USMC innovation labs and the adoption of new technologies. For this purpose, we studied the Marine Corps’ commitment to establish AM and innovation cells and bolstered this effort through an array of educational modules that illustrate best practices aimed at technology exploration and how these spaces might avoid obstacles to technology adoption.

Findings and Conclusions

This project addressed following research questions:

First, how can NPS support the innovation mission of the Marine Maker Movement? We propose a multiprong approach to that end: (1) active collaboration between USMC innovation cells and NPS Robodojo Lab (exchange of expertise and training materials); (2) collaboration between Marine Corps Systems Command (MCSC) and NPS Center for Additive Manufacturing (both research and education mission, including student thesis, sharing of Center’s materials and resources); and (3) a series of field visits that would support ongoing data collection and acquire undated understanding about the innovation and technology adoption.

Second, what types of innovation approaches (including technologies) would be of best use for the Marine Corps’ new Innovation Labs? We advise the following major approaches to support innovation and to instigate and reinforce large-scale technology adoption:

General approaches: (a) Design and implement a phased approach to technology adoption and innovation; (b) Identify and promote short term and long term goals; (c) Whenever possible support elements of self-sustainability and scalability (example: train the trainer concept); (d) Distribute efforts, resources, programs and infrastructure across the service, with minimal centralization of resources; (e) Promote program activities; (f) Instill elements of follow-up and address users’ concerns early on; (g) Support innovation and technology adoption while deployed and while in the base.

Training: (a) Generate high-quality training modules and resources, and make them available to adopters; (b) Establish a multi-tier approach to training.

Innovators and adopters: (a) Instill a strong sense of ownership among innovators and adopters; (b) Ensure visibility and promote their efforts; (c) Recognize and reward their results; (d) Design challenges, community projects, and competitions that allow users to cement innovation lab knowledge into real-world projects.

Innovation portal: (a) Establish a multifaceted innovation portal that will not only store the data needed for daily work and collaboration among innovation cells but also generate metrics about the scale and health of innovation efforts across the service; (b) Provide incentives and ensure continuous data collection in innovation portal.

Technologies: (a) additive manufacturing; (b) basic electronics; (c) robotics; (d) software; programming; (e) circuit board design and printing.

Third, what types of hands-on lab experiences would be of most use to Marine Corps Innovation Labs, and how should these experiences be developed and disseminated? Our project team designed and created several instructional modules focused on theoretical approaches and practical topics of great interest to leadership cadres of innovation cells and Marines, who will collaborate and innovate individually and in teams. Those modules are made available to the topic sponsor, as well as NPS students and faculty. Modules that review theoretical approaches leverage our knowledge about adoption and innovation theories and data sets that we collected in the past. Due to the rapidly developing situation associated with Covid-19 and limited interaction with the innovation cells, we were not able to execute our planned field trips.

We created the following narrated modules:
AM background, slicers, printers and troubleshooting and part scanning Introduction to Raspberry Pi, Arduino, Fusion360 LiPo battery safety How to build a computer Technology adoption: Theory and best practices Innovation by domain users.

Recommendations for Further Research
As it is the case with the diffusion of innovation, these types of studies are always longitudinal—no innovation or technology adoption happens overnight, especially not in a large group of domain users; multiple years of consistent activity in domain, combined with the data collections among diverse groups of potential innovators and adopters, are needed to achieve that goal.

We recommend applying an iterative design process that would include (a) design of new approaches specially crafted to augment and increase the efficiency of innovation effort across the United States Marine Corps (USMC); (b) ongoing data collection in an innovation portal (activities of innovators and innovation cells); (c) data analysis and, if needed, a re-design and application of new and updated approaches.

The following open questions also need to be addressed in the future:
How can innovation cells get the base management as well as unit leaders onboard and get their commitment and long(er) term support for the most productive work of those groups? How can they persuade the management to take the risk? How can innovation cells attract people to self-select and engage in the work of those groups? What mechanisms of incentives and rewards could be established on the level of service (USMC), military base, and unit? (Note: a majority of people in innovation cells are self-selected.) How does the lack of both local and global personnel and training policies and funding

impact innovation and technology adoption including the return on investment (ROI)?How can larger naval enterprise ensure that additive manufacturing laboratories adopt and practice the characteristics of the outward-oriented institutions? (Outward-oriented groups are those innovation cells not hesitant to reach out to potential customers, i.e., active duty units, and collaborate with other innovation cells; they do it on regular basis and in an organized way.) How do we capture lessons learned in innovation cells, distribute them, and share with other groups? What type of incentives could be provided to ensure that lab personnel create that type of material and shares their experiences?

2020 posed a number of challenges, and our limited travel and limited lab access narrowed our ability to meet our vision for this project. In the ideal 2020, we would have fostered a stronger tie with Innovation Labs that were looking to adopt new technologies, and we would have a had a better understanding regarding questions about technologies of interest. In the future, we would recommend a stronger iterative back and forth to ensure that our training materials met the exact needs of Innovation Labs. We would be thrilled to consider future opportunities to support these cells and to share new materials as we develop them.

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List of Abbreviations and Acronyms

3D - three-dimensional
3D - three-Dimensional
5G - 5th generation wireless systems
AAW - Anti-Air Warfare
ACE - Air Combat Element
ADMITS - Alcohol Drug Management Information Tracking System
ADOC - Advanced Division Officer Course
ADRAM - Airframe Depot Readiness Assessment Model
AFP - adaptive force package
AFSIM - Advanced Framework for Simulation, Integration, and Modeling
AGI - Artificial General Intelligence
AGM - aircraft ground mishaps
AI - Artificial intelligence
AI/ML - Artificial Intelligence/Machine Learning
A-II - Aircraft Inventory Exhibit
AIP - air-independent propulsion
AJAX - Asynchronous JavaScript and XML
AM - additive manufacturing
ANUSD - Automated Navy Unclassified Software Distribution
Ao - operational availability
APDF - Aircraft Program Data File
API - Aviation Preflight Indoctrination
APT - Advanced Persistent Threat
AR - augmented reality
ARG - amphibious ready group
ARGUS - Audit Record Generation and Utilization System
ASCM - Anti-Ship Cruise Missile
ASM - Anti-ship Missile
ASTB - Aviation Selection Test Battery
ASTM - American Society for Testing and Materials
ASUW - Anti-Surface Warfare
ASW - anti-submarine warfare
ATEAR - Aircraft Towing Enhanced with Augmented Reality
ATF - Amphibious Task Force
ATT&CK - Adversarial Tactics, Techniques & Common Knowledge
AUV - autonomous underwater vehicle
AVIA - Autonomy, Validation, Introspection, and Assessment
AWS - Amazon Web Services
BDOC - Basic Division Officer Course
BEMOS - Bayesian ensemble model output statistics
BF - Blue Force
BFC - Bulk Fuel Cache
BFH - budgeted flight hour
C2 - command and control
C2D2E - Command and Control in a Denied or Degraded Environment
C4 - Command, Control, Communications, Computers
CA - Cognitive Assistant
CA - Complex, Adaptive
CAA - Annual Capability Area Assessment
CALDERA - Cyber Adversary Language and Detection Engine for Red-team Automation
CARF - Combat Active Replacement Factor
CARF-STAT - CARF Statistical Analysis Tool
CASPER - Coupled Air-Sea Processes and Electromagnetic ducting Research
CCDR - Combatant Commander
CD&I - Combat Development and Integration
CDR - Commander
CDT - CONOPS Development Team
CEC - Cooperative Engagement Capability
CENETIX - Center for Network Innovation and Experimentation
CISD - Center for Innovation in Ship Design
CIWS - close-in weapon system
CLF - combat logistics force
CNA - Center for Naval Analysis
CNAF - Commander, Naval Air Forces
CNO - Chief of Naval Operations
COA - course of action
COLREGS - Collision Regulations or International Rules of the Road

List of Abbreviations and Acronyms Cont.

COMBATXXI - Combined Arms Analysis Tool for the 21st Century
COMSUBPAC - Commander, Submarine Forces, Pacific Fleet
COMSUBFOR/LANT - Commander Submarine Force United States Atlantic Fleet
COMSURFDEVRONONE - Commander, Surface Development Squadron ONE
CONN - Conning Officer
CONOPS - concept of operations
CONUS - Continental U.S.
COTS - Commercial-off-the-shelf
COVID - coronavirus disease
CPH - cost per hour
CPU - Central processing unit
CRISP-DM - Cross-Industry Standard Process for Data Mining
CSDS1 - Commander, Surface Development Squadron ONE
CSR2 - Cognitive Sensing, Radio, and Radar
CTF - Capture the Flag
CUSV - Common Unmanned Surface Vessel
CVN - aircraft carrier (nuclear propulsion)
CW - Continuous Wave
CWS - Cyber Warfighting System
DAU - Defense Acquisition University
DCI - Deputy Commandant for Information
DDG - guided missile destroyer
DE - Directed Energy
DEA - Drug Enforcement Agency
DEOCS - Defense Equal Opportunity Organizational Climate Survey
DFG - derelict fishing gear
DIK - Data-Information-Knowledge
DL - Deep Learning
DLT - Distributed Ledger Technology
DM - Decision Maker
DMDC - Defense Management Data Center
DMO - Distributed Maritime Operations
DNN - Deep Neural Network
DoA - direction of arrival
DOD - Department of Defense
DoDIN-N - Department of Defense Information Network-Navy
DoN - Department of Navy
DOTMLP - Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities
Dr. - Doctor
DRAM - Depot Readiness Assessment Model
D-UNS - Deliberate Universal Need Statement
DYSMAS - Dynamic System Mechanics Advanced Simulation
EAB - Expeditionary Advanced Base
EABO - expeditionary advanced base operations
EDRAM - Engine Depot Readiness Assessment Model
EMRG - Electro Magnetic Railgun
EMS - electromagnetic spectrum
EO - electro-optical
ERG - engine readiness goal
ERM - Enterprise Risk Management
ESSM - Enhanced Sea Sparrow Missile
EUCOM - U.S. European Command
EW - electronic warfare
EWG - Executive Working Groups
FA - Functional Area
FAA - Federal Aviation Association
FCT - Fleet Collaborative Team
FHP - Flight Hour Program
FOR - field of regard
FOV - field of view
FPGA - Field Programmable Gate Array
FRC - Fleet Readiness Center
FRP - Fleet Response Plan
FRS - Fleet Replacement Squadron
FRTP - Fleet Response Training Plan
FSCn - Fire Support Coordination
FUSED - Fuel Usage Study Extended Demonstration
GAO - U.S. Government Accountability Office
GCE - Ground Command Element
GCSS-MC - Global Combat Support System-Marine Corps
GenOC - generalized optimal control
GEOINT - geospatial intelligence
GNSS - Global Navigation Satellite System
GPS - Global Positioning System

GSOIS - Graduate School of Operational and Information Systems
HBCU - historically black colleges and universities
HELCAP - High Energy Laser Counter-ASCM Program
HELIOS - High Energy Laser with Integrated Optical Dazzler and Surveillance
HMAM - Hierarchical Marine Assignment Model
HMD - head-mounted display
HMT - Human-Machine Teaming
HPM - High Powered Microwave
HQMC - Headquarters, Marine Corps
HVP - hypervelocity projectile
HYCOM - Hybrid Coordinate Ocean Model
ICBM - Intercontinental Ballistic Missile
ICOP - Intelligence Carry-On Program
ICS - Industrial control system
ID - identification
IETMs - interactive electronic technical manuals
IFS - Introductory Flight Screening
IM - Instant Message
IMU - inertial measurement unit
INDOPACOM - Indo-Pacific Command
INOCCS - Integrated Navy Operations Command and Control System
INS - Inertial Navigation System
IOC - Indicators-of-Compromise
IOC - Initial Operational Capability
IP - Internet Protocol
IPCL - Integrated Prioritized Capabilities List
IPR - Internal Progress Review
IR - infrared
IREF - Initial Research Estimate Form
IS - information systems
ISD - Instructional System Design
ISR - intelligence, surveillance, and reconnaissance
IWC - Information Warfare Community
JCEC - Joint Cooperative Engagement Capability
JF - Joint Fires
JIATFSouth - Joint Interagency Task Force South
JOOD - Junior Officer of the Deck
JP-4 - military specification 50–50 kerosene-gasoline blend
JP-5 - military specification kerosene-based shipboard jet fuel
JP-8 - military specification kerosene-based universal (air and ground) fuel
JTRS - Joint Tactical Radio System
KM - knowledge management
KR - Knowledge Representation
LAILOW - Leverage AI to learn, optimize, and win game
LaWS - Laser Weapon System
LCDR - Lieutenant Commander
LDUSV - large displacement unmanned surface vessel
LED - Light Emitting Diode
LEO - low-earth orbit
LFM - Linear Frequency Modulation
LHA - landing helicopter assault ship (United States Navy hull classification)
LHD - landing helicopter dock ship (United States Navy hull classification)
LiFi - Light Fidelity
LLA - Lexical Link Analysis
LLP - Lessons Learned Program
LMACC - Lightly Manned Autonomous Combat Capability
LNA - Logistical Network Analysis
LNG - Liquified Natural Gas
LOCE - littoral operations in contested environments
LPD - Landing Platform/Dock
LT - Lieutenant
LUSV - Large Unmanned Surface Vessel
M/LUSV - Medium and Large Unmanned Surface Vessels
MACO - Master of Applied Cyber Operations
MADL - Multifunction Advanced Data Link
MAGTF - Marine air-ground task force
MALE - Medium Altitude Long Endurance
MBSE - Model-Based Systems Engineering

List of Abbreviations and Acronyms Cont.

MC - Mission Capable
MCA - Multi-Criteria Analysis
MCC - Model-Computed CARF
MCDA - Multi-Criteria Decision Analysis
MCIOC - Marine Corps Information Operations Center
MCM - mine countermeasures
MCO - major combat operations
MCPC - Marine Corps Program Code
MCRC - Marine Corps Recruiting Command
MCSIL - Marine Corps Spectrum Integration Laboratory
MCWL - Marine Corps Warfighting Laboratory
MDA - maritime domain awareness
MDUSV - Medium Displacement Unmanned Surface Vehicle
MEAD - Mission Engineering and Analysis Department
MEMS - microelectromechanical systems
MEU - Marine Expeditionary Unit
MIDS - Multifunctional Information Distribution System
MIG - Marine Expeditionary Force Information Group
ML - Machine Learning
MLD - Maximum Likelihood Estimation
MLE - Maximum Likelihood Detection
MMOA - Manpower Management Officer Assignments
MOE - measure of effectiveness
MOP - measure of performance
MOR - Measure of Risk
MOS - Model output statistics
MOT - Measure of Trust
MSC - Military Sealift Command
MUSV - Medium Unmanned Surface Vessel
N/A - not applicable
NAS - Naval Air Station
NATO - North Atlantic Treaty Organization
NAVAID - Navigational Aid
NAVAIR - Naval Air Systems Command
NAVEUR - Naval Forces Europe
NAVSLaM - Navy Atmospheric Vertical Surface Layer Model
NDR - Network Detection Response
NF&LCFT - Naval Fuels & Lubricants Cross Functional Team
NIST - National Institute of Standards and Technology
NIWC-Pac - Naval Information Warfare Center-Pacific
NLP/U - Natural Language Processing/Understanding
NLW - non-lethal weapons
NOA - Naval Operational Architecture
NOFORN - No Foreign Nationals
NPS - Naval Postgraduate School
NRP - Naval Research Program
NRWG - Naval Research Working Group
NSA - Department of National Security Affairs
NSFS - Naval Surface Fire Support
NSS - Naval Simulation System
NSS - Navigation, Seamanship, and Ship-handling
NSW - Naval Special Warfare
NSWC - Naval Special Warfare Command
NWP - Numerical weather prediction
OAD - Operations Analysis Directorate
OCO - offensive cyberspace operations
ODIN - Optical Dazzling Interdictor, Navy
OMB - Office of Management and Budget
OOD - Officer of the Deck
OODA - Obseve, Orient, Decide, Act
OPNAV - Office of the Chief of Naval Operations
OSHA - Occupational Safety and Health Administration
OSS - Officer Selection Station
OST - Officer Selection Team
OT&E - Operational Test and Evaluation
P&R - Programs and Resources
P/PM - performance/pricing model
PBFT - Practical Byzantine Fault Tolerance
PCS - Permanent Change of Station
PET - Polyethylene terephthalate
PI - Principal Investigator
PLA - Polylactic acid

List of Abbreviations and Acronyms Cont.

PLAN - (China's) People's Liberation Army Navy
PLC - Power Line Communication
PMA - post mission analysis
POF - Probability of fail
POL - Petroleum, oil and lubricants
POM - Program Objective Memorandum
POSSE - Program of Ship Salvage Engineering
POWer - organization simulation system
PPBE - Planning, Programming, Budget, and Execution
QCP - Qualified Candidate Population
QPSK - Quaternary Phase Shift Keying
RASP - Replenishment at Sea Planner
RCR - Radar-to-Communications Ratio
RF - Radio Frequency
RF - Red Force
RF - random forests
RFH - required flight hour
RHEL - Ruggedized High Energy Laser
RNCOM - Regional Navy Ocean Coastal Model
ROE - rules of engagement
ROI - Return on investment
RoR - Rules of the Road
Rx - Receive
SA - situation awareness
SAM - surface to air missile
SAR - synthetic aperture radar
SAW - Simple Aggregate Weighting
SBIR - Small Business Innovation Research
SCADA - Supervisory Control and Data Acquisition
SEAL - Sea, Air, and Land Teams
SER - Symbol Error Rate
SFC - Single Fuel Concept
SIEM - Security Information and Event Management
SIGMAN - signature management
SIGS - School of International Graduate Studies
SM-2ER - Standard Missile-2 Extended Range
SM-2MR - Standard Missile-2 Medium Range
SM-3 - Standard Missile-3
SM-6 - Standard Missile-6
SMM - Ship Maintenance Model
SMWDC - Naval Surface and Mine Warfighting Development Center
SNA - Social Network Analysis
SNLWS - Surface Navy Laser Weapon System
SNMA - Systematic Narrative Meta-Analysis
SOAR - Security Operations Automation Response
Soar-RL - Soar reinforcement learning
SOF - U.S. Special Operations Forces
SOM - Ship Operations Model
SoS - System of Systems
SRBR - Symbol Rate to Bandwidth Ratio
SSL - Secure Sockets Layer
SSL-TM - Solid State Technology Maturation
STORM - Synthetic Theater Operations Research Model
STRONG - signature, threat, risk to OPSEC, narrative, gains from mitigation
SUM - sense, understand, maneuver
SWAP - space, weight and power
SWAP-C - Size, Weight, and Power - Cooling
SWSC - Surface Warfare Officer Schools Command
T/M/S - type/model/series
TACSIT - Tactical Situation
TAMCN - Table of Authorized Material Control Number
TCP - Transmission control protocol
TD - tow crew director
TEI - total engine inventory
TEU - twenty-foot equivalent unit
tkMS - thyssenkrupp Marine Systems
TLAM - Tomahawk Land Attack Missile
TLS - Transport Layer Security
TMS - aircraft type, model, and series
TPS - Transactions per Second
TRADOC - United States Army Training and Doctrine Command
TRIM - total readiness integration model
TSK - Turkish Armed Forces
TSSE - Total Ship Systems Engineering
Tx - Transmit
UAS - unmanned aerial system
UAV - unmanned aerial vehicle

List of Abbreviations and Acronyms Cont.

UEBA - User and Entity Behavior Analytics
UI - User Interface
UMV - unmanned maritime vehicle
UNCLAS - Unclassified
UNDEX - underwater explosion
UNREP - underway replenishment
USA - United States Army
USAF - United States Air Force
USCG - United States Coast Guard
USFF - United States Fleet Forces Command
USINDOPACOM - United States Indo-Pacific Command
USMC - United States Marine Corps
USN - United States Navy
USSOCOM - United States Special Operations Command
USV - unmanned surface vessel
USW - undersea warfare
UUV - Unmanned Underwater Vehicle
UXV - Unmanned Vehicle
VCS - Visual Commonsense Graphs
VLA - vertical launch antisubmarine
VLS - Vertical Launch System
VR - virtual reality
WIP - Warfare Improvement Programs
WMAM - Weighted Marine Assignment Model
WRENCH - Workbench for refining Rules of Engagement against Crowd Hostiles

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