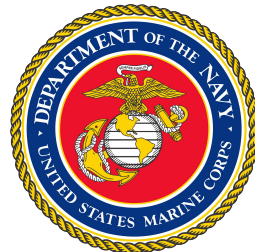




NAVAL RESEARCH PROGRAM
SHARPENING THE SPEAR
NAVAL POSTGRADUATE SCHOOL



2019 ANNUAL REPORT



FISCAL YEAR 2019 ANNUAL REPORT



NAVAL RESEARCH PROGRAM

NAVAL POSTGRADUATE SCHOOL

July 2020

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MESSAGE FROM THE DEAN OF RESEARCH

I am pleased to support the Naval Postgraduate School (NPS) Naval Research Program (NRP) in the fifth complete fiscal year of the program. The studies sponsored within FY19 have made significant contributions to the Department of the Navy (DoN) by providing insights to key operational decision-makers along with recommendations to support cost savings in a fiscally constrained environment. The NRP's funding and program goals are directly in line with SECNAV's goal to provide research to "support[s] the Navy in reaching well-informed, objective decisions on strategic, operational, and programmatic issues through collaborative research."

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 2019 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 2019, execute new work this year, and plan for future projects, it is appropriate to acknowledge and thank the NRP staff members who are responsible for organizing a great program. This year, in particular, we thank and say farewell to our National Capital Region NRP Representative, CAPT (Ret) Bob Osterhoudt, whom is enjoying full retirement in North Carolina. We thank him for his many years of dedication to not only NRP but to NPS, the Navy, and our nation.

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 OPNAV 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 and in coordination with the Navy Analytic Office (NAO). 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 50 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 480 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 FY19, \$11.6M, in funding distributed, which translated into 84 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. To date, over 320 faculty and military faculty from all four academic schools have joined 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 193 United States and foreign thesis students collaborating with faculty on 54 of the 84 projects.

*Executive summaries for six FY18 projects are included in this annual report but are not reflected in the FY19 Annual Report statistics.

FY19 Research Highlights

The FY19 research aligns with the recently released NPS Strategic Plan and the 2018 National Defense Strategy. The FY18 TRB implemented a business rule to encourage collaboration across both Navy and Marine Corps Topic Sponsors. That decision recognized that the NRP should address broader naval issues. The NPS Strategic Plan signed in April 2018 recognizes that the most impactful research areas are those that address the core challenges facing both the Navy and the Marine Corps.

Accordingly, the research highlights are grouped by topic area...

DATA SCIENCE AND MACHINE LEARNING

The Naval Research Program funded studies related to data science and machine learning. Some studies were combined to serve both the Navy and Marine Corps. Study NPS-19-M103-A: The Running Estimate (RE) for the MEF Command Element and NPS-19-N333-A: Provisioning of a Multi-int Fusion Environment in the Era of AI and Machine Learning recognized the value of dynamically extracting and projecting operationally relevant events like environmental data to enhance a commander's ability to make informed decisions to ensure battlefield success. Ultimately, this research revealed a layered ontology for describing the battlespace in a way that provides real-time decision support, and enables COA development and assessment by human warfighters, and ultimately, by artificial intelligence (AI).

INNOVATION

In line with the broader focus on innovation, the Naval Research Program delivered in key areas. Innovation is the adoption of a new practice within a community. Some studies focused on understanding innovation to align with the Navy's efforts to address fundamental changes to its strategic focus to maintain its maritime superiority in an increasingly volatile and uncertain environment. Study NPS-19-N001-A: "Maritime Strategy and Naval Innovation" explores the emergence and implications of near peer geostrategic competition with a focus on the Indo-Pacific region. Study NPS-19-N304-A: "Enhance Warfighter Performance by Fostering Organizational Agility & Innovation in the Naval Research and Development Enterprise" considers increased organizational innovation and agility across the Navy bureaucracy to deliver the latest technology to the warfighter.

CYBER

In Cyber, studies provided tailored answers to the challenges facing the naval service to organize cyber and electronic warfare and the technologies needed to manage these new capabilities in terms of infrastructure and specialized warfighter skills. Studies NPS-19-N036-A: CYBER/RF MILDEC in Naval Operations and NPS-19-M185-A: Optimized Network Emulation of Signals Intelligence (SIGINT) and Tactical Cyberspace Environments for MAGTF Training were combined to serve both the Navy and Marine Corps. In this research, training techniques and technologies for cyber/RF military deception were investigated, and scenarios for distributed cyber/RF operations were designed. Additionally, nodes were emulated for tactical communications with state and non-state actors, and command operations were evaluated in a congested signals intelligence and cyberspace environment.

TALENT MANAGEMENT

Talent management studies highlighted various common concerns shared by the Navy and the Marine Corps through the lens of each organization's culture and practices. Several studies examined talent management by looking at the drivers and incentives of organizational and occupational commitment and best practices. For the Navy, the need for a market-based retention and assignment process was explored in NPS-18-N314-A: Design of an Enlisted Assignment & Retention Marketplace. Study NPS-19-N347-A: Assessing Executive Leadership Development: Leaders, Leadership Teams, and Command Agility sought to identify factors that facilitate or impede the mission alignment and effectiveness in the command transition processes at the flag level. Study NPS-19-M268-A: Creating and Maintaining a Specialized Occupational Force: Marine Information Environment Operations identified the challenges/opportunities for managing talent by analyzing a Marine Operations in the Information Environment (OIE) military occupational specialty (MOS) and how should they be addressed.

ACQUISITION AND LOGISTICS

The acquisition process determines appropriate materiel solutions for the requirements for the DoD. Study NPS-19-N248-A: Mission Scenario Generation and Characterization to Support Acquisition Decision for Long Range Precision Fires-Maritime (LRPG-M) helps with conception and consideration of system requirements early in design. Other research such as NPS-19-N176-A: AoA Paradigm for Early Visibility of Logistics and Cost in the Acquisition Process focused on using Analysis of Alternatives (AoA), a study comprising a crucial part in the process of acquiring a new system for the DoD. The NRP supports the core service function of equipping the force, and NRP studies provide the analytical foundation for decision makers and planners to optimize what is acquired and how it is supported.

GLOBAL STRATEGY

The National Defense Strategy signed in 2018 focuses on the return of strategic competition and its impact on U.S. strategy. The FY19 research aligned with the National Defense Strategy. NRP projects such as NPS-19-N001-A: Maritime Strategy and Naval Innovation (Continuation) focus on the emergence of near peer geostrategic competition which has become the central planning focus for the Navy as it considers its plans, programs, budgets and policies over the rest of this century. Other studies like NPS-19-N134-A: Implementing the DoN 30-Year R&D Plan: Creating and Sustaining a Culture that Values Learning, Strategic Agility, Collaboration and Innovation addressed the importance of aligning strategies supported by appropriate organizational structures, tasks and practices, with those of training, education, informal continuous learning, rewards and incentives. Both of these studies focus on naval responses in support of the National Defense Strategy.

ASN(RDA) - RESEARCH, DEVELOPMENT, AND ACQUISITION

NPS-19-N003-A: Counter Directed Energy Warfare (CDEW)

Researchers: Dr. Joseph Blau, Ms. Bonnie Johnson, Dr. Keith Cohn, Mr. John Green, and Mr. Gary Parker

Student Participation: Mr. James Ansley CIV, Mr. Kyle Buffin CIV, Ms. Victoria Couture CIV, Mr. Eranga Gonaduwege CIV, Mr. Stephen Hakimipour CIV, Ms. Lisa Nguyen CIV, Mr. Ernest Murray CIV, Mr. Ryan Kee CIV, Mr. Trevor Lutz CIV, and Mr. Michael Schwitzing CIV

Project Summary

Through a process of data gathering, concept development, and analysis, this project conducted a high-level study of the naval tactical Counter Directed Energy Warfare (CDEW) domain. The purpose of the study was to better understand the future directed energy (DE) threat environment, potential effects on naval assets, and to develop conceptual CDEW solutions. The results of this study provide a knowledge foundation for the Office of Naval Research and the naval DE community.

Keywords: *directed energy, high energy lasers*

Background

Recent DEW developments by China and Russia have prompted the study of strategies and capabilities for countering these potential threats. Reports from as recently as May 2018 cite that China has been developing laser weapons “ranging from low-powered tactical beam emitters to a high-energy strategic weapons system (Zhen, 2018). China’s laser systems include: (1) ground or vehicle-based systems with 10kW of power that can destroy small fixed-wing aircraft, helicopters, and drones at low altitudes and short ranges (2km); (2) a larger 30-100kW vehicle-based system with a larger range (4km); (3) a vehicle-based electro-optical system to support early warning, missile guidance, and lethal capabilities; and (4) individual low-power laser guns that can dazzle or blind an enemy from a short range. It was also reported in May 2018 that two U.S. pilots were injured after military-grade lasers were aimed into their eyes from China’s naval base in Djibouti (Zhen, 2018).

In March 2018, a leading Russian defense official confirmed that laser weapons, alluded to by President Vladimir Putin, are in service and capable of disarming targets with rapid precision (O’Connor 2018). While less is openly known about Russian DEW capabilities, it has been reported that Russia is working on aircraft-mounted lasers as part of an “anti-satellite complex” (Killalea, 2018), and a ground vehicle-based high-energy laser (mounted on “massive low-bed wheeled trailers”) possibly for anti-missile defense.

The potential consequences of adversarial DEW capabilities are numerous. They could affect military communications through anti-satellite and anti-electronic capabilities and situational awareness by blinding or dazzling our sensors. They could also attack drones, small aircraft, helicopters, and small

boats. These capabilities could be harmful to the Navy's ability to operate in maritime and littoral regions, and they affect naval logistics and support platforms.

Various technologies and strategies have recently been considered for countering DEWs. Technological approaches include target hardening such as reflective coatings, and the use of materials with improved thermal properties and exotic metamaterials that can potentially bend electromagnetic waves around a target (Hewitt, 2017). Strategic approaches include evasive maneuvers, deployment of decoys or obscurants, and swarm attacks.

Findings and Conclusions

Two capstone projects by Naval Postgraduate School (NPS) master's students in systems engineering are underway to support this research project. The first student team is studying the potential effects of a future DE threat environment on naval unmanned aerial vehicles (UAVs) (Ansley et al., 2019, 2020). This group started its project during the summer 2019 quarter and will finish in March 2020. They are studying UAV vulnerabilities in an adversarial DE environment, and are developing and evaluating concepts for CDEW strategies and methods that can defend naval tactical UAVs against DEW threats. A second student team, who will graduate in September 2020, has begun performing a similar study for manned naval aircraft (Murray et al., 2020).

This study began the process of understanding the possible future DE threat environment. This task was organized into four categories: possible adversarial DE threats, threat characteristics, naval tactical assets at risk, and naval tactical mission affected. This research is still underway, with a white paper report (Johnson, 2020), and a related presentation (Johnson, 2019), that will be made at the Directed Energy Professional Society Symposium in November 2019.

This project included a high-level study of DE threat identification, or DE combat identification (CID). A need was identified for tactical warfighters to be made aware of DE threats in the operational environment. Three types of DE CID were identified and studied: first, a preventative DE CID in which intelligence, surveillance, and reconnaissance means would find possible adversarial DE weapons before they are used, second, a real-time detection ability that can identify active DE weapons being used in an operational environment, and third would be a battle damage assessment capability to identify that a naval asset had been lased after the fact—perhaps as the target of a laser soft-kill or hard-kill. A DE CID capability could include the ability to determine attribution—identifying the specific adversary responsible for a DE attack. The capability could also include identifying threat classification to determine the type of DE weapon and characteristics such as power level.

One purpose of this project was to study CDEW methods and strategies that can be used to defend naval tactical assets against potential adversarial DE threats. A literature review and discussion with subject matter experts identified several methods, including: the use of protective coatings and materials, atmospheric and environmental effects to obscure and protect assets, decoys and countermeasures, and a concept for implementing swarms of UAVs for safety in numbers. Research in this area is ongoing via student capstone projects.

This study identified an additional outcome that could support the recently initiated NPS DE modeling and simulation (M&S) project. The M&S project is modeling a variety of naval tactical operational scenarios involving high-energy lasers. This CDEW project produced adversarial DE threat scenarios that can be used to analyze the DE environment, as well as support DE wargaming in the M&S system. The

M&S project could include models of adversarial DE threats, models of the effects of these threats on naval assets, and models of CDEW strategies and methods.

Additionally, the M&S could model both soft-kills and hard-kills as well as anti-satellite, anti-UAV, anti-aircraft, and anti-ship DE weapons.

Recommendations for Further Research

This study lays the foundation for further research in the following areas: DE threat characterization, DE threat identification, development of CDEW methods and strategies, and CDEW modeling and simulation.

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NPS-19-N085-A: Modeling and Simulation for Lifetime Predictions

Researchers: Dr. Bryan O'Halloran and Dr. Douglas Van Bossuyt

Student Participation: Mr. Matthew Morningstar CIV

Project Summary

Service life assessments and reliability predictions for electronics need early design phase improvement to avoid uncertainties, inaccurate results, and poor design decisions. This research paper presents a merged

probabilistic physics of failure (PoF) approach to account for the physical location of microelectronics, and determine the resulting time-to-failure based on randomly placed failure mechanisms. A case study using a generic circuit card assembly and corrosion related failure mechanisms exhibits the utility of the merged probabilistic PoF approach. The results demonstrated that the location of microelectronics can impact the time-to-failure for a circuit card assembly, because a failure mechanism's probability of occurrence increases or decreases based on changes in temperature and humidity. Additional research and analysis using actual test results should be performed to verify the accuracy of these results, and to account for additional failure mechanism types.

Keywords: *reliability predictions, physics of failure, PoF, probabilistic, failure mechanisms*

Background

In the last few decades, there has been increased pressure on the electronics industry to increase the performance of their chips, while decreasing their physical size. This results in an increased number of transistors per chip, and increases the number of reliability issues primarily due to higher current densities (Varde, 2010). The increased complexity in electronic devices drives the need for more accurate and robust prediction methodologies to improve service life assessments. Traditional methods for predicting reliability or time-to-failure such as those found in MIL-HDBK-217F, notice 2, are well documented and widely used by practitioners; however, they are often inaccurate compared to the reliability of fielded devices, and do not account for uncertainties. Some inaccuracies can be attributed to mis-understanding the initial source data for the application, environmental conditions, operational modes, and lack of understanding of the detailed design (Gu & Pecht, 2007).

In support of improving service life assessments and reliability predictions for electronic and complex hardware systems, this research investigated the development of a model for predicting the expected life of parts. Specifically, this research uses PoF models for electronic devices, incorporates a probabilistic approach to account for the uncertainties due to variations in parameters, and accounts for the location failure mechanisms. The goal is to determine and merge the impacts due to multiple failure mechanisms and improve the accuracy of the service life assessment. For purposes of this research, PoF is based on principles of science and technology, and provides the insight into not only life and reliability aspects of the component, but also provides details about the various degradation mechanism(s) and thereby improved understanding of the associated root cause(s) of the failure.

Findings and Conclusions

This research can help the Navy and design engineers by providing a methodology and process to predict where failure mechanisms are more likely to occur, and improve the service life and time-to-failure for microelectronics early in the design phase. The merging of the two or more failure mechanisms is only practicable if they occurred in the same location.

The first step of the process was to identify the potential failure mechanisms based on the operational modes and environment. For example, we chose to assume that corrosion and Electromigration were likely to occur based on high temperatures (e.g. >85°C) and relative humidity levels in excess of 85%. Typical operating temperature range for military electronics is -65°C to +125°C. Given the assumed failure mechanisms, the likely locations of occurrence were identified on the circuit card assembly, which allowed the area of the circuit card assembly to be randomly sampled for thousands of iterations using a Monte Carlo simulation. The results from the simulation were analyzed and the number of cases where

one or more failure mechanisms were present was determined. When multiple failure mechanisms were found, the resulting time-to-failures were merged.

Based on experience, simply adding the time-to-failure for two failure mechanisms seems too conservative, but it is typically preferred over being overly optimistic, which could result in a large logistics burden.

The results demonstrated that the location of components can have significantly impact a circuit card assembly's service life due to an increased likelihood of one or more failure mechanisms. From a design perspective, if the operational environment (e.g. stressors) and likely location of failure mechanism occurrence is understood upfront and early in the design, the time-to-failure or service life can be significantly increased.

Recommendations for Further Research

Further research and analysis based on actual test results is required to better understand the likelihood of multiple failure mechanisms occurring within the same region or location of a component or device. The data would allow for more experimentation to determine if one or more failure mechanisms are likely to occur within the same location or region, and increase the confidence of merging results. Additionally, there needs to be more experimentation to determine the optimal method for combining failure mechanisms. For example, it may not be optimal to add the time-to-failures for multiple failure mechanisms. It may be more realistic to use a weighted average based on their likelihood of occurrence.

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NPS-19-N134-A: Implementing the DoN 30-Year R&D Plan: Creating and Sustaining a Culture That Values Learning, Strategic Agility, Collaboration and Innovation

Researchers: CDR Sue Higgins USN Ret., Dr. Donald Brutzman, Ms. Ann Gallenson, and Dr. Gail Thomas

Student Participation: Ms. Susan Alderson CIV

Project Summary

In 2017, a 30-year Department of Navy (DoN) Research and Development (R&D) Plan addressed concerns among Navy leaders about increasing the technological advantage and maritime superiority of the fleet in a dynamic security environment. The plan was developed collaboratively by a multi-organization group, led by the Director of Strategy and Innovation, Deputy Assistant Secretary of the Navy (DASN) for Research, Development, Test and Evaluation (RDTE). That group, reframed as the RDTE Strategic Thinking Community of Interest (ST-COI), met in an interactive webinar/teleconference

two to four times each month from 2017 to 2019. In that time, it grew from 25 to 250 members, and focused on “future horizon scanning” of 5-30 years.

It considered emerging trends and technologies, while discussing how corresponding implications, risks, opportunities, and challenges might impact Naval capabilities. This effort resulted in an informational archive of over two gigabytes on the Department of Defense (DoD) collaboration platform, All Partners Access Network. This project observed and evaluated the ST-COI as a way to develop an acquisition workforce that values continuous learning beyond mandatory refresher training.

The following questions guided our work:

1. How might the Naval Research and Development Establishment (NR&DE) improve and accelerate the implementation of the DoN 30-Year Research and Development Plan?
2. How might NR&DE leaders develop a workforce and culture that values continuous learning to open minds and challenge paradigms, and collaboration, innovation, and strategic thinking to promote organizational agility?

In addressing these questions, we built on previous research, participated in ST-COI webinars/teleconferences, and collaborated on design, development and delivery of a multi-day workshop at the Naval Postgraduate School (NPS). We found that communities of interest and practice can serve as a valuable, continuous learning complement to formal education and training opportunities.

Keywords: *Naval Research and Development Establishment, NR&DE, agility, innovation, communities of interest, COIs*

Background

The ST COI webinar/teleconference agendas included wide-ranging topics that provided a broad awareness of the strategic environment, and the anticipated implications of emerging technologies for DoN capabilities. Topics included: agile methodology, augmented reality, autonomous systems, blockchain, cloud computing, cognitive warfare, cyber security, data analytics, digital currency, internet of things, machine learning, mobile computing, neuroscience, quantum computing, social media. Additionally, global strategic issues and changes in society, work, economy, health, and learning were discussed.

Several articles and reports were also discussed in each session from sources such as: Harvard Business Review, Forbes, Nature, Science, The Economist, RAND, MITRE, National Science Board, World Economic Forum, McKinsey, Council on Foreign Relations, Center for Strategic and Studies, Naval Studies Board, House Armed Services Committee, Defense Advanced Research Projects Agency, Defense Innovation Board, United Nations, OPNAV N2/6, OPNAV N3/5, and vision, policy and strategy documents from Air Force, Army, Navy, Marine, DoD (e.g.: Education for Seapower, Design for Maritime Security, National Defense Strategy, National Security Strategy). Additionally, the findings of several in-person workshops hosted at NR&DE Warfare Centers were summarized and discussed (e.g.: Naval Warfare Systems Command Application Integration Workshop, NPS’ Warfare Innovation Continuum, Acquisition Research Program, Naval Research Program, Naval War College program on warfighting technology integration).

In December 2018, the Navy released “Education for Seapower (E4S)” in which Under Secretary of the Navy Thomas Modley highlighted in a memorandum “Continuous learning—and sharing hard-won knowledge —represents a combat-proven key to victory for our naval services.”

However, the focus of E4S is uniformed members of DoN, not the Navy’s civilian scientists and engineers who comprise the NR&DE’s acquisition workforce (AWF). Continuous learning (CL) for the AWF is addressed in DoD Instruction 5000.66, which requires that “all AWF members must engage in at least 80 hours of CL every two years” (Department of Defense [DoD], 2017). While these recertification requirements enable the AWF to keep up with changing structures, resources, policies, and procedures necessary to manage acquisition programs, they do not address how emerging technologies impact the Navy’s ability to fight and win wars.

Findings and Conclusions

In an increasingly volatile, uncertain, complex and ambiguous (VUCA) world, the Navy’s success will depend on developing a culture that values learning, strategic agility, collaboration and innovation. This will require strategies supported by appropriate organizational structures, tasks and practices, with alignment of training, education, informal continuous learning, rewards and incentives.

The scientists and engineers of the Navy’s AWF comprised of more than 2000 PhDs, are highly skilled in their individual science and engineering disciplines. In a VUCA world in which technology advances are increasingly led by the global commercial market, how might the AWF broaden awareness in interdisciplinary technology advances that are necessary for the Navy to fight and win wars? We found that COIs and communities of practice (COPs) can serve as a valuable, continuous learning complement to formal education and training opportunities.

The military services are experimenting with COIs and COPs, such as the Navy’s ST-COI and the Army’s Mad Scientist. Educational theorist Etienne Wenger considers COPs, a term he coined, as a robust strategy for professional learning, since knowledge sharing and narration of work make implicit knowledge more visible, and new ideas often come from diverse networks outside the organization (1998). Essentially, COIs and COPs enable the integration of work and learning.

Recommendations for Further Research

As the E4S is explicit in recognizing the value on continuous learning for the DoN further efforts should be made to continue and expand the ST-COI as a continuous learning opportunity for DoN. For example, the Naval X organization in the office of the DASN for Research Development and Acquisition’s and the Navy’s Chief Learning Office could explore possible organizations as host-facilitators, and consider the NPS and/or the Naval War College as site. Additionally, research could be conducted to create a holistic Naval education strategy that includes the Navy’s civilian workforce, especially the scientists and engineers of the acquisition workforce. In tandem, exploration of how COIs and COPs can add value to the acquisition workforce by expanding knowledge sharing across DoN, DoD, and the federal government would be a valuable effort.

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NPS-19-N247-A: Investigation of Railgun Bore Wear after Prolonged Exposure to a Marine Environment

Researcher: Dr. Andres Larraza

Student Participation: LT Daniel Baxter USN

Project Summary

Deployment of a shipboard Railgun will revolutionize naval gunnery by providing high launch velocity without the use of propellant or rocket motors, which will enable long range, reduced time to target, and kinetic energy kills. The Hyper-Velocity Projectile (HVP) will provide the Navy with a highly accurate and affordable multi-mission projectile that can be fired from multiple gun systems. With a GPS-guided HVP, a Railgun Weapon System provides high volume Strike Warfare and Naval Surface Fire Support at ranges in excess of 100 nautical miles. These missions support Marine, Army or Special Forces ashore, and place the nation on the “right side” of cost curve to engage long range, volume fires against low- and high-end threats from near-peer competitors, particularly when compared against missiles or tactical aircraft. When integrated with sensors and command & control systems, HVP will also have Anti-Air Warfare capability, where the higher launch speed of Railgun will enable Cruise Missile Defense and Ballistic Missile Defense. Not only does the higher Railgun launch speed enable maneuverability overmatch to engage very challenging threats, it permits faster time to target - aiding combat decision timelines, and better management of the missile inventory to address the most stressing threats. In order to meet the Chief of Naval Operations’ demand for “Speed to Fleet,” work must begin in earnest to examine Railgun shipboard integration requirements, mount design and development, and analysis and integration of system capabilities. Notably, lack of information about Railgun corrosion is delaying the TRL-6 system demonstration required for a Milestone B Decision.

Keywords: *railgun, hyper-velocity projectile, HVP*

Background

Railguns are uniquely capable of achieving very high muzzle velocities as compared to conventional guns. The Office of Naval Research railgun program has demonstrated prototype barrels up to 2.5 km/s muzzle velocity (Mach 7.5), while laboratory railguns have operated to greater than 5 km/s. Electromagnetic launch development is outpacing that of conventional guns. Experts agree that the limits of conventional guns for navy ship technology have been reached, while Railgun technology is truly at the beginning of its technology maturation.

Findings and Conclusions

The final report details the classified results of a study, conducted at the NPS Railgun Lab – the largest railgun experimental facility of any US academic institution – in collaboration with the Naval Research

Lab and NSWC Dahlgren, to determine the effects of marine corrosion on Railgun performance. The conclusions are documented in the SECRET manuscript, “Effect of Corrosion on Bore Life and Armature Performance,” which was accepted after peer review to the Hypervelocity Gun Weapon System Workshop, and in the SECRET MS Thesis of LT Daniel Baxter.

NPS-19-N304-A: Enhance Warfighter Performance by Fostering Organizational Agility & Innovation in the Naval Research and Development Enterprise

Researchers: CDR Susan Higgins USN Ret., Dr. Donald Brutzman, Ms. Ann Gallenson, Dr. Erik Jansen, and Ms. Brittany Ramsey

Student Participation: Ms. Susie Alderson CIV

Project Summary

The Chief of Naval Operations’ (CNO) Design for Maritime Superiority identifies concerns about unprecedented and accelerating rates of change in maritime systems, global information systems, and technology. It highlights the need to reexamine approaches in every aspect of the Navy’s operations. The National Defense Strategy is a clear call to action: accelerate the delivery of technology to the warfighter. To this end, Naval leaders are calling for increased organizational agility across the Navy bureaucracy. In support of these calls, our work explored how the Naval Research and Development Establishment (NR&DE), including a key organizational stakeholder, might increase organizational innovation and agility in an environment that is increasingly volatile, uncertain, complex and exponentially accelerating (E-VUCA).

The following questions guided this research:

- How can NR&DE leaders foster organizational and individual capacity for agility and innovation such that its workforce can adapt to an E-VUCA environment to ensure the Navy’s warfighting superiority?
- What are the cultural and organizational implications across the NR&DE of accelerating rates of technological change?
- How might agile teams and intrapreneurship opportunities contribute to expanding innovation and agility in the NR&DE?

In answering these questions, we built on previous research. With Commander, Operational Test & Evaluation Force (COTF), a key stakeholder of the NR&DE, we explored ways to improve their organizational capacity for agility and innovation. We considered how the NR&DE, which is comprised of the Naval Warfare Centers and Labs, and other stakeholders might leverage existing resources at Naval Postgraduate School (NPS) to improve capacity for organizational agility and innovation. We collaborated on design, development and delivery of a multi-day workshop on complex adaptive systems at the NR&DE Naval Surface Warfare Center, Carderock Division.

Our results, captured in a white paper and technical research report, indicated that because agile practices are not appropriate for all work, it is important to assess when they should be used. Our white paper

provides lessons from industry leaders, including that leaders should understand that modifying roles, as opposed to structural change, can promote the collaboration needed by agile development processes. Additionally, implementation of agile goals can depend on leaders' ability and willingness to be agile themselves, instead of relying on traditional methods of control. This calls for leaders to cultivate an increased tolerance for risk and ambiguity throughout the RDT&E environment when agile processes are employed, while valuing and rewarding continuous learning.

Keywords: *Naval Research and Development Establishment (NR&DE), agility, innovation, agile processes, agile organizations*

Background

In a recent Naval Institute Proceedings article, retired U.S. Marine Corps General John Allen describes a hypothetical "hyperwar" scenario in which decision times are reduced to seconds. In the scenario, a guided-missile destroyer is confronted with cyberattacks driven by artificial intelligence (AI) and waves of swarming autonomous systems, which overwhelm the crew and devastate the ship in minutes (Allen & Husain, 2017). This scenario is conceivable given the confluence of four rapidly changing technologies: cloud computing, AI, big data and internet of things. Former U.S. Secretary of Defense, Robert Gates, views this confluence as an "existential threat" that should both alarm leaders, and be viewed as "an historic opportunity" for changing the Navy's efforts in research, development, test and evaluation of future weapon systems. Calls by the CNO and other Navy leaders to increase the Navy's capacity for agility and innovation are rooted in this and similarly plausible scenarios.

However, declarations by senior leaders to increase the Navy's agility alone do not lead to necessary change; transforming large organizations is a complicated process. Leaders must align strategy, organizational structures, tasks, practices, training, education, informal continuous learning, rewards, and incentives, all while considering interdependencies across these categories.

Our previous work discussed organizational culture as revealed to leaders and members of organizations by shared assumptions that emerge largely, although not entirely, in response to leadership actions that impact policies and actions in five domains: (1) strategies and goals, (2) structures, (3) practices and technologies, (4) training and education, and (5) reward systems and incentives. Organizational culture emerges out of the sensemaking of individual interactions in response to leadership's communications and "sense-giving." Thus, leaders shape, but do not control, culture. Therefore, attempting to induce culture change through partial, non-systemic efforts may produce limited compliance, but it is unlikely to generate the deeper commitments required for lasting changes in values and norms. Building on this work, we explored what leaders should consider as they attempt to shape an agile and innovative naval culture.

Findings and Conclusions

Our white paper reviews business cases of corporate exemplars for agile practices and assessments, particularly in large organizations that confront the challenges of bureaucracy. It includes an action plan that provides considerations for leaders who are attempting to shape an agile and innovative naval culture. The paper also cautions leaders implementing agile approaches that: (1) not all work is appropriate for agile methods, (2) large complex organizations can have both agile teams and traditional units, (3) implementing agile goals is unlikely to be successful if leaders use traditional methods of

hierarchical control and formalized planning, (4) leaders should consider changing roles, rather than structures, to promote the cross-functional collaboration needed when employing agile methods.

Navy experiments leveraging other transactional authorities have also been identified to potentially catalyze innovation and increase the agility in some areas of the NR&DE. For example, Naval Innovation in Science and Engineering funding is helping to increase research on rapid prototype development, experimentation and demonstration across the NR&DE (National Defense Authorization Act for Fiscal Year 2017, 2016). Additionally, the recently formed Naval-X, a small team that reports to the Assistant Secretary of the Navy for Research, Development and Acquisition, serves as a Department of Navy (DON) workforce "super-connector" focused on scaling non-traditional agility methods across the DON workforce.

Lastly, a challenge facing the Warfare Centers and Labs which comprise the NR&DE and its stakeholder COTF, is the inclusion of the customer's "voice" early and often into RDT&E processes, a necessity when agile methods are employed. COTF has recognized that NPS students will test and evaluate these systems, acting as operational customers. A follow-on Naval Research Program project with COTF will explore bringing NPS students-as-customers onto projects earlier and more often than previously.

Recommendations for Future Research

There are several areas for future research, including developing an Organizational Agility Maturity Model appropriate for the NR&DE, and building capacity within NR&DE to develop agile mindsets. Also, applying agile practices when appropriate by developing workshops, courses, and certificates, for Science, Technology and Engineering and Math workforce to learn about agile methods and their application to programs and projects within the NR&DE, and increasing the leverage of NPS research, experimentation, and learning venues by NR&DE organizations.

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NPS-19-N354-A: MIMO Transmission Capabilities to Increase Data Transmission Rates Between Disconnected Tactical Entities

Researchers: Dr. Gurminder Singh, Mr. Charles Prince, and Mr. Peter Ateshian

Student Participation: Maj Paul Keeley USMC, and Maj Eric Stewart USMC

Project Summary

The strength of the highly networked Joint Force to apply lethality at the lowest level requires the ability to communicate data from the tactical edge. Threat actors throughout the world have developed sophisticated electronic warfare techniques, which can be used to jam or target friendly radio-frequency (RF) emissions; therefore, the Joint Force needs to develop options for tactical communications in a RF-denied environment. One option to augment existing communications systems is the use of free space

optical (FSO) communications, which employ a high bandwidth, narrow beamwidth channel, characterized by a low probability of detection and interception. This could have significant military applications, ranging from communications between dispersed tactical units to datalink capacity between surface units and aerial relays. However, FSO communications in the atmosphere are characterized by additive white Gaussian noise and turbulent fading, which combine to significantly reduce the usable throughput of such a channel.

Our research affects the Naval Information Warfare community, and supports the pillar of Assured Command and Control. As such, it describes theoretical system requirements for overcoming these problems, while simultaneously increasing throughput, based on a multiple input/multiple output (MIMO) FSO channel. Several key systems architecture decisions are highlighted, and a full factorial design architecture of experiments is used to explore the breadth of the design space. Optimal candidate architectures are then identified through a tradeoff analysis between the bit error rate (BER), transmission rate, and power consumption. The principal coding-related research question was determining how a combination of forward error correction (FEC) encoding techniques might be applied to improve the reliability and efficiency of the MIMO FSO communications channel. This portion of the research tested thirteen coding and modulation schemes in software under different simulated levels of noise and turbulence, to determine which characteristics of the codes most critically affect performance. The results identified the probability of outage of such a MIMO channel as the most significant channel parameter. Additionally, we found that MIMO architectures employing more than eight sub-channels provide significantly increased protection against turbulent fades.

Keywords: *systems engineering, information sciences, free space optical, FSO, multiple input/multiple output,*

Background

As a high bandwidth, narrow beamwidth channel, FSO communications can potentially achieve high data rates with a low probability of detection and intercept. Single input, single output (SISO) systems such as the Tactical Line-of-Sight Optical Network, are currently being pursued by the Department of Defense. However, SISO systems are susceptible to line of sight limitations, and high levels of atmospheric loss. MIMO optical systems, on the other hand, have the potential to overcome these limitations by providing spatial diversity and redundancy to the transmission.

This research explores ways to take advantage of this diversity and redundancy to efficiently and effectively encode transmissions. Possible use cases include: communications between dispersed tactical units such as reconnaissance elements, firing units or scout observers and short-term, high-rate datalink capacity between surface units and unmanned or manned aerial relays. Ranges could vary from less than 500 m (as in a dispersed artillery battery), to 10 or more kilometers (as when conducting expeditionary advanced base operations).

Andrews and Phillips (2005) describe the atmospheric FSO channel in depth, and its communication application challenges are also noted by Chan (2006), Kaushal and Kaddoum (2015) and Alouini, Yang and Gao (2014). Mitigation techniques include diversity, FEC, and multi-user scheduling, respectively. Application of two-dimensional codes to an array of FSO transmitters was recently experimented with at the Naval Postgraduate School by Adrian Felder (2018), who used a dynamic sequence of Quick Response (QR) codes to pass data between an array of light emitting diodes and a camera.

This research extends the QR experiments by examining a wide variety of array sizes and coding schemes, and comparing each proposed architecture against a realistic channel model. Hypotheses testing involved varying the code scheme, number of lasers, modulation scheme, laser wavelength, detection threshold levels, signal to noise ratio (SNR), and level of turbulence on the channel. The overall expectation was that as SNR and turbulence decreased, any given channel would become increasingly usable.

Within this performance curve, increased numbers of lasers combined with increased levels of FEC should result in more resilient communications with a decrease in efficiency.

Findings and Conclusions

This research applied rigorous simulation testing to several theoretical predictions, and as such, the two principal research areas were divided into coding theory and systems architecture. Data was collected through simulation in both portions, and three basic categories of codes were identified and implemented in software, along with a simulator based on a statistical channel model. Two categories (repetition and Reed-Solomon codes) are found in the literature, and a third category, which combined a temporal channel code with various spatial line codes, was devised for this research. These corresponded to high-, low- and mid-rate codes, respectively. Overall, thirteen different coding schemes were tested during the simulation phase. Previous work using QR codes was also evaluated probabilistically.

The goal of the systems engineering portion was to identify significant architecture decisions needed to support the development of engineering prototypes. It quantified the significant impact to the system performance of design decisions, including array size, wavelength, modulation scheme, coding scheme, and threshold detection levels, given a range of various atmospheric conditions. These atmospheric conditions included noise and turbulence, and was simulated using the same model as in the coding portion. The systems engineering analysis identified significant main effects and second-degree interactions. Each of the architecture decisions had a statistically significant impact on the system's BER. The irradiance threshold had significant second-degree interactions in concert with the coding scheme, SNR, and the number of lasers. Two additional system measures of performance included the transmission rate and the power efficiency. The tradeoff analysis identified the best performing architectures in terms of BER; within this group, a tradeoff between transmission rate and power efficiency was analyzed to provide the recommended candidate architecture in each turbulence regime.

Our research shows that under weak turbulence conditions, a high-rate coding scheme paired with on-off keying offers the best protection against the minimal effects of the optical channel, while increasing the transmission rate beyond that of a repetition code. As turbulence increases, the code rate must decrease, therefore, in strong turbulence, a repetition code across some level of spatial diversity is required. When implemented accordingly, the impairments of reduced probability of detection, increased probability of the channel being in a fade, and the extended duration of the fades can all be overcome.

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 employ FSO communications systems under conditions of turbulence and noise. Field programmable gate arrays offer the flexibility to program and develop a system capable of operating at the transmission speeds required in the modern operating environment.

Also, while both portions of this research indicated that large array sizes are required for improved transmission, smaller array sizes may be feasible given a shorter anticipated link length. Other improvements could be made by relaxing the hard-decision requirement and implementing various forms of soft-decision decoding. Convolutional codes were not considered by this research, but they may prove to be an attractive variable-rate option for the outer code, and low-density parity check codes may also be considered for the outer code.

Additionally, algorithmic complexity was not specifically addressed in this research, but future prototyping should take advantage of existing optimizations for several of the codes used.

Implementing interleaving at a greater depth may be useful in low to moderate turbulence cases where the channel is degraded, but not in an outage. If a padding scheme is used to fill the interleaver when data demands are low, interleaving may help overcome the effects of noise at the price of latency, memory and possibly channel overhead. Lastly, inter-layer protocols could be developed to take advantage of the decoding statistics and coordinate retransmission of data prior to transmission-control protocol (TCP) detection of packet failures. This may help obviate the concerns identified by Chan (2006) in which TCP requests significantly affected throughput.

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NPS-19-N393-A: Development of Shipboard Equipment Shock Survivability Assessment Technique (Continuation)

Researchers: Dr. Young Kwon and Mr. Jarema Didoszak

Student Participation: No students participated in this research project.

Project Summary

Navy ships are expected to perform their mission in an arduous combat environment. Shock loading from non-contact explosions is one of many mechanisms that have the potential to cause extensive damage to these vessels. In particular, underwater explosions (UNDEX) resulting from mines, torpedoes, or other waterborne explosive devices pose considerable risk not only in structural failure, but also in terms of equipment damage, personnel casualties and ultimately mission kill. So critical is this issue that the Navy has outlined shock-hardening requirements for surface combatants in OPNAVINST 9072.2A. Per this instruction, the Naval Sea Systems Command (NAVSEA) established general guidelines for the

verification, validation, and certification of surface ship shock hardness in the technical publication T9072-AF-PRO-010. While this document establishes a general method of shipboard equipment shock qualification, standardized criterion that delivers a survivable design requires improvement to minimize existing uncertainty.

To this end, the initial effort of this study focused on assessment of the current technique so as to investigate uncertainties in the shock level response experienced during the shock qualification process as compared to the actual failure parameters. Using basic analytic approaches and finite element modeling and simulation, key parameters influencing the response and uncertainty in failure prediction were ascertained. The next effort focused on development of an improved guideline to enhance the survivability of shipboard equipment subjected to realistic UNDEX loading conditions. This was accomplished by developing unified criteria for functional failure of equipment, which were validated using computer modeling and simulation. These results generated a standardized procedure for the determination of shock-related failure in shipboard equipment. The suggested approach can be applied across various shipboard equipment and systems in the evaluation of shock hardness.

Keywords: *UNDEX, underwater explosion, FSST, shock hardening, equipment survivability*

Background

The purpose of the surface ship shock hardening program is to ensure that U.S. Navy combatants are capable of performing their mission whilst subjected to underwater explosion events. As design level live-fire testing is not practical for vessels of this type, the ship system, comprised of the ship structure, equipment and crew, must be tested in a representative manner in order to verify its performance under realistic UNDEX conditions.

Currently, two main paths exist to provide shock qualification of shipboard equipment: a) incremental reduced level explosive testing and b) assessment by other means of verification.

Of these, some argue that live-fire testing is by all means the closest representation to the actual combat event, as it produces an explosive shock loading and thus must be mandated for shock verification. However, this is not necessarily the case. Typical live-fire testing options, which consist of the heavyweight or floating shock platform (FSP) shock test, as it is more commonly known, and the full ship shock trial (FSST), which is considered to be the gold standard of shock testing by some (though not even a qualification test), do not replicate design level shock loading, but are merely representative in nature. Thus, neither of these two approaches may actually result in the desired outcome, which is the accurate prediction of how a specific equipment or system, as installed within the ship will perform, given a threat level shock loading condition.

The MIL-DTL-901-E, which provides the basis for shock qualification testing, offers additional options to vendors in order to demonstrate that their equipment is acceptable for shipboard use in a shock environment. However, it lacks definitive criteria beyond the simple categories of non-operational, visually damaged etc., that would lead to a “failure” rating. There is no quantitative performance rating for the equipment being tested in most cases, unless specifically called out as an additional requirement in the contract. To drive out this type of uncertainty, an improved acceptance guideline is necessary; as a result, the objective of this project was to develop a new procedure for shock-hardened equipment.

Findings and Conclusions

Ultimately, the desired outcome is to link representative shock qualification testing of shipboard equipment to the actual response performance of the equipment in a realistic shock environment without having to place the ship in peril. Through the systematic analysis of recorded qualification test data, a more reliable assessment of shipboard equipment response can be achieved. By requiring the measurement of dynamic response parameters of equipment undergoing qualification testing through instrumentation accelerometers, strain gauges, etc., a threshold value can be established. In the case of a successful test conducted in accordance with the MIL-DTL-901E, where the equipment continued to operate as required, the measured critical response values in this study are used for comparison with simplified equipment models exercised in a realistic full ship shock scenario via validated finite element modeling and simulation (M&S) techniques. By comparing equipment model response in the simulation against those measured from physical testing, using the newly developed unified criteria for functional failure, a conservative estimate of true shock survivability can be made. Furthermore, this bridging of measured and simulated response at the equipment level provides a means of focusing on potential equipment response in different loading conditions, placements and orientations than were realized through the limited physical testing.

The general procedures for implementing this new approach to the existing shock qualification standards are summarized here. If a piece of equipment is to be shock qualified for shipboard installation and use, the following procedure is recommended:

1. Prepare equipment in accordance with MIL-DTL 901-E procedures for shock validation of shipboard equipment based on grade, class, weight, form factor, etc.
2. Apply accelerometers to test article, or velocity meter, if practical, to record base input motion to equipment scheduled for test.
3. Measure physical response (acceleration, velocity, strain) away from the base.
4. If the equipment passes current test requirements, proceed with the following. If it does not, modify, redesign and retest the equipment.
5. Create a reduced-order multi-degree of freedom (MDOF) equipment model via modal analysis (system identification procedure) using existing FEM model, if available.
6. Evaluate MDOF model in fully coupled ship shock FEM simulation using recorded 901 Series data (installed accelerometer, velocity meters, strain gauges as input, or desired shock scenarios is unavailable).
7. Place equipment at planned installation locations within the ship model, if known.
8. Extract acceleration, velocity and displacement response values from M&S.
9. Validate equipment against both the known failure limit (physical result from current 901 Series test, ensuring visual pass) and the new failure criteria based on maximum velocity and change in displacement.

Recommendations for Further Research

The criteria developed for functional failure of shipboard equipment was validated using numerical modeling and simulation. For additional confirmation, a series of experimental tests are recommended in order to further validate these functional failure criteria.

N1 - MANPOWER, PERSONNEL, TRAINING & EDUCATION

NPS-18-N314-A: Design of an Enlisted Assignment & Retention Marketplace

Researchers: Dr. William Gates, Dr. Kenneth Doerr, and CDR William Hatch USN Ret.

Student Participation: No students participated in this research project.

Project Summary

The Navy needs a market-based retention and assignment process that is capable of meeting the Navy's job, career, and quality needs, while also meeting the sailors' individual desires, preferences, and aspirations. Focusing on the enlisted Aerographer's Mate community, this research proposed five alternatives to introduce more market-based mechanisms into the enlisted detailing process, specifically: three alternative auction designs, two-sided matching, and two-sided matching with money. The traditional reenlistment and assignment processes address both retention and assignment, but they face significant risk for under- or over-estimating the retention incentive needed to meet end-strength goals, are inflexible, do not reward performance, and include a portion of less than voluntary assignments.

For example, a basic auction approach offers precision in setting retention and assignment incentives at the exact minimum level necessary to achieve the desired outcome; it can also be modified to incorporate adjustments for past or predicted future sailor performance, or to include individualized non-monetary incentive packages to further improve performance. However, auctions do not specifically address the one-to-one nature of the Navy's assignment process. Two-sided matching and two-sided matching with money are specifically designed to address this assignment problem. We find that two-sided matching with money provides the best performance of all alternatives across the relevant performance metrics, and best fits the Navy's preferences for an enlisted detailing marketplace.

Keywords: *enlisted detailing, enlisted assignment, enlisted retention, market-based assignment.*

Background

There is substantial literature, mostly authored by Naval Postgraduate School (NPS) faculty and students, which analyzes auctions as an alternative to the Navy's traditional retention and separation processes. There is also substantial literature, again mostly authored by NPS faculty and students, analyzing two-sided matching as an alternative to the Navy's traditional assignment process. This is the first attempt to simultaneously address retention and assignment with a more market-based process, wherein sailors and commands can directly or indirectly work out terms and conditions for jobs and enlistment contracts.

Findings and Conclusions (to include Process)

The Navy needs a market-based retention and assignment process that is capable of meeting the Navy's job, career, and quality needs, while also meeting the sailors' individual desires, preferences, and aspirations. A more market-based process would have several key features:

- Buyer/seller negotiation: more opportunities for sailors and commands to directly or indirectly work out terms and conditions for jobs and enlistment contracts.

- Multiple/flexible options: a greatly expanded set of options and opportunities available to sailors and commands.
- Changing prices and incentives: Commands and sailors can negotiate a wide range of monetary and non-monetary incentives as part of the assignment “package” to ensure the most qualified sailors fill all jobs.
- Voluntary choice: probably the key element of a marketplace, brought about by the flexible incentives, options, and negotiation between sailors and commands.

Considering the important influence that retention and assignment incentives exert on Navy talent-management objectives, it is essential to develop criteria comparing alternative courses of actions (COAs). This analysis assesses alternative COAs against six performance metrics:

1. *Precision*: assignment/retention incentives should accurately meet talent-management objectives, including overall end-strength and sailor distribution across assignments.
2. *Voluntary*: assignment/retention incentives should be structured such that each service member willingly accepts the proposed assignment, and perceives that compensation for the assignment is both satisfactory and fair.
3. *Flexible and Responsive*: assignment/retention incentives should be flexible enough to adjust resources quickly and effectively in response to emerging issues, shifting priorities, and changing market conditions.
4. *Best Value*: assignment/retention incentives should provide cost-effective solutions to address specific Navy needs while minimizing cost. Best value involves identifying the minimum cost incentive packages and target those qualified service members most willing to serve in the proposed assignment.
5. *Support Achievement*: assignment/retention incentives should successfully compete for talent, reward performance, and recognize sailors’ contributions to the Navy’s mission.
6. *Practicality*: practicality in retention and assignment programs addresses the ease of implementation for the Navy and ease of service member participation.

It is important to note that retention and assignment have traditionally involved two separate processes. Retention seeks to maintain the right number and quality of sailors by rank and occupation. The assignment process involves pairing sailors with billets or assignments in a “one-to-one matching” problem as each sailor can match with at most one billet and vice versa. As a result, when comparing market-based COAs, we must evaluate their ability to address both retention and assignment issues, along with aligning projected rotation date and end of active obligated service date.

This research examined six COAs:

- COA 1 – The traditional reenlistment and assignment programs.
- COA 2 – A basic auction design, modeled here as a uniform-price, sealed-bid, reverse auction with a single unit supply. Sailors would bid over the retention incentive required for them to supply their labor to the Navy, with the lowest bidders retained and paid the bonus requested by the first excluded bidder.
- COA 3 – A quality-adjusted discount action design, where “quality discounts” are given to the bids from high-performing sailors, effectively making them more likely to be retained in the auction. The discount is then added back to their retention incentive if they are retained, giving them a quality premium over the other retained sailors.

- COA 4 – A combinatorial auction, where sailors can include both monetary and individualized packages of non-monetary incentives in their required retention incentive bids. In this COA, sailors have an incentive to include non-monetary incentives in their bids if the value they receive exceeds the Navy’s cost of said incentives.
- COA 5 – A basic two-sided matching process, where sailors submit a rank-order preference list over the billets they are willing to accept, and commands submit similar rank-order lists over the sailors they prefer. An algorithm makes assignments based on these lists, ensuring the resulting assignments are stable; no participant is matched to an unacceptable partner, and no two unmatched participants would prefer to be matched to one another, as opposed to their respective partner identified through the process.
- COA 6 – A two-sided matching with money process where sailors submit “bids” reflecting the minimum bonus required for any billet they would willingly fill, and the Navy (commands) submits “offers” to qualified sailors reflecting the maximum bonus they would pay each sailor to fill each billet. An algorithm again makes assignments based on the sailors’ and Navy’s bids and offers, and the resulting assignments are stable.

Each of the six COAs described above is informally graded for each of the six performance metrics, and each was discussed in terms of its ability to address the retention and assignment aspects of the enlisted detailing market place.

Given our analysis, for an enlisted assignment and retention marketplace, two-sided matching with money is the COA that best fits the Navy’s preferences. Further, it is possible to align projected rotation date and end of active obligated service for AG sailors during their second term of enlistment, which would support an enlisted detailing marketplace.

Recommendations for Further Research

First, the assignment and retention process can potentially span several iterations for any particular sailor, and since prior research has not examined the impact this may have on sailors’ bidding strategies, this should be explored. Second, for the three auction formats, past research has both simulated the auction performance and experimentally examined how sailors can be expected to bid in these auctions. However, a particular sailor could win multiple auctions, which would require the Navy to develop an assignment algorithm. It is unclear how this assignment mechanism will affect bidding strategies, and this should be explored experimentally.

NPS-19-N212-A: Intuitive System Training

Researchers: Mr. Perry McDowell and Dr. Meghan Quinn Kennedy

Student Participation: No students participated in this research project.

Project Summary

The schools under the Naval Education and Training Command (NETC)’s cognizance are committed to producing the best possible sailors for the fleet. To this end, it is important for NETC to collect accurate information regarding how well the training and education sailors receive at various schools applies to

their current job duties. Currently, assessment surveys are disseminated to all graduates from NETC-affiliated schools and the graduates' supervisors at their first duty station. The staff at NETC is concerned that this method potentially faces sampling challenges and measurement errors due in part to Department of the Navy (DoN) policies and regulations. These challenges and errors then lead to inaccurate results, and low confidence in those results, which is especially important now because NETC is leading the Navy's transition to Ready, Relevant Learning (RRL). The shift to RRL will require NETC to make significant changes to current training practices, and NETC needs reliable data during this change—otherwise, the organization might not recognize significant training lapses, or could make decisions based upon flawed data.

To examine these challenges, we reviewed the literature on survey design and management. From this literature review, we created a summary of best practices in survey design and management, and investigated whether NETC's current practices are producing the kind of results to correctly assess the performance of its schools.

Keywords: *Surveys, training effectiveness, Naval Education and Training Command, NETC, Job/duty task analysis, JDTA, Ready Relevant Learning, RRL*

Background

The current methods used to create the survey sent to graduates and their supervisors is based upon the job/duty task analysis (JDTA) for each rating that NETC educates in either an "A" or a "C" school. From this JDTA, NETC personnel work with subject matter experts to create a subset of approximately 20–30 tasks pertinent to that rate, and ask three questions about each task: how frequently the sailor performs it (rated on a "Daily," "Weekly," "Monthly," etc. scale), how proficient the sailor is at it (rated from "Needing training" to "Able to train others"), and how adequate the sailor believes the training to be (rated from "Highly adequate" to "Not at all adequate").

Current response rates to these surveys are fairly low: 20% return by the graduates and 10% for their supervisors. NETC desires to know whether the low response rate means that the data derived from these surveys is inadequate: As RRL is phased in across the fleet, NETC must have a method of determining whether this new training paradigm is producing sailors at the same or higher levels than previous training methods. Thus, NETC needs to know whether current survey methodology is sufficient; if not, it must attempt to find methods to overcome the causes of the low response rates. NETC has identified several difficulties in administering the surveys, accounting in part for low response rates:

- The surveys are sent directly to the sailors. NETC does not know (and it is not practical to obtain) the identity of the graduates' direct supervisors; it therefore sends the surveys to the graduates' commands and trusts that the chain of command will direct them to the correct individuals. Thus, for the surveys to reach the proper supervisor, several events need to occur correctly which often do not. Most recently, the NETC command career counselor has begun sending the surveys to the command master chiefs and command career counselors of the ships in the hopes that this will result in a larger portion of the supervisors' surveys being returned, but this change is too new to determine its efficiency.
- NETC wants graduates to take the survey after they have been in their jobs for at least three months, and it is precluded from surveying graduates more than twelve months after graduation.

Considering that most sailors take a month to reach their next duty station, often spending three months in non-rate duties (e.g., working on mess decks), this leaves a small window to reach the graduates and their supervisors.

- The Office of General Counsel has ruled that the sailors and their supervisors cannot be forced to complete these surveys. This is despite the fact that reviewing the performance of sailors serving under them is the responsibility of every sailor in the fleet.

Much is known about best practices in survey design and implementation (Bethlehem & Biffignandi, 2012), and some work has been done that specifically addresses surveys for military populations (Buttrey et al., 2011; O'Connor et al., 2011). In this research, we developed guidance regarding sampling procedures, survey design and implementation, and data processing that can be used to refine NETC's current methods, with the goal of obtaining greater confidence in the assessment survey results. We also indicate areas in which DoN policies and regulations are impeding NETC's ability to collect accurate information on these assessments from a representative sample.

Findings and Conclusions

To investigate this issue, we conducted a literature review of the research regarding survey responses and design. We focused on topics directly related to the NETC's goals of attaining accurate survey assessment results from a representative sample of graduates and supervisors: sampling design, survey design, and data processing. We published a technical report with our complete findings and recommendations (Kennedy & McDowell, 2019). The highlights are presented below:

A. ATTAINING A REPRESENTATIVE SAMPLE

It is important that the sample of survey participants is representative of the population of interest; in the case of NETC, the populations of interest are (1) all graduates from NETC in the past several months and (2) all personnel who are currently the direct supervisors of these graduates. Both sampling design and response rates can impact the extent to which a representative sample is attained.

B. ATTAINING ACCURATE DATA

Attaining accurate data requires not only a representative sample, as discussed above, but also the reduction of measurement error. Bethlehem & Biffignandi (2012) outline the types of errors that can lead to inaccurate survey results, including sampling error, overcoverage error, undercoverage error, nonresponse errors, and two common forms of measurement and processing errors—memory errors and satisficing. Satisficing is filling out the survey as quickly as possible without giving much consideration to the questions; this often manifests itself as the respondent filling in either all the lowest or highest responses.

C. DATA PROCESSING

Data processing is essential for ascertaining whether a representative sample and accurate data were obtained. Data processing entails collecting and analyzing paradata—data that is generated while participants complete the survey. Examples of paradata include the time taken to answer each question, which keys are pressed, and whether or not participants used any help functions. Paradata can either be maintained on the server (server-side) or on the client's machine (client-side).

Recommendations

We recommend that NETC make the following modifications to its survey procedures in order to improve the three areas we covered in our findings:

A. SAMPLING PROCESSES

- Goal: To increase the number of people in the population of interest who receive the survey request; to reduce potential undercoverage or overcoverage.
- Comments: Due to the NETC's current method for disseminating the survey to the supervisors, the supervisor who receives the survey may not be the direct/correct supervisor for the targeted graduate. However, NETC cannot ascertain how often the wrong supervisor completes the survey. This issue leads to concerns of potential undercoverage of direct supervisors and overcoverage of non-direct supervisors.
- Recommendations: In the email that is sent directly to the graduate, provide two links: one that the graduate uses to complete the survey and one that they send to their supervisor. This way, NETC will have confidence that the survey was sent to the correct supervisor.

B. RESPONSE RATE

- Goal: To ensure an appropriate response rate is achieved for both the graduate and supervisor surveys.
- Comments: Adequacy of the response rate is tied to sample representativeness. A 10% response rate may be sufficient if the sample is representative. Making completion of the survey mandatory can be problematic both in terms of DoD policies and instructions, and in terms of increasing the likelihood of satisficing.
- Recommendations:
 - Ask CRESST to provide descriptive statistics on survey demographic information to ascertain if the sample of responders is representative of the population of interest. If the sample is representative, then the low response rate is of less concern.
 - Per results from Newell, Rosenfeld, and Harris (2004), offering an incentive, such as recommendation for a liberty card to those graduates and supervisors who complete the survey, may increase response rates.
 - Per results from Newell et al. (2004), providing a summary of the survey results and any changes to trainings based on the survey results to the survey respondents may, in the long term, increase response rates. This information also can be used in the survey request to future cohorts of graduates and supervisors as a way to demonstrate that NETC takes their opinions seriously.

C. SURVEY DESIGN

- Goal: to increase accuracy of responses and reduce measurement errors.
- Comments:
 - The majority of the survey design follows best practices: the survey follows a logical order, only one question is shown at a time on the web version, and the response options for the frequency and proficiency questions are clear and logically spaced.

- However, some wording is a little confusing. For example, in the adequacy and quality question, no distinction between “adequacy” and “quality” is provided. The definition for the “Excellent” response option is unusual and may confuse participants. Finally, verb tenses are sometimes inconsistent within a given question.
 - Additionally, due to the timing of when the survey can be distributed, respondents might not accurately remember the information solicited by questions dealing with both the frequency and the adequacy/quality of training. However, this issue appears to be inherent in survey administration limitations that are outside of NETC’s control.
 - The appendix in Kennedy and McDowell (2019) provides specific comments on a supervisor survey. Many of these comments also apply to the graduate surveys.
- Recommendations that apply to both graduate and supervisor surveys:
 - On the adequacy/quality of training questions, remove the word “adequacy” and clarify the definition for the “Excellent” response option, perhaps replacing it with “training enabled me to perform all parts of the skill competently.”
 - On the web version of the survey, provide a link next to each response option or to the center-right of all response options that, when clicked on, provides the definition for each response option.
 - On the general questions about your/your subordinate’s performance, use the same verb tense used in the question for all response options.
 - To reduce potential memory effects, start the frequency questions with the sentence, “Think back on your time in this job.”
 - To reduce potential memory effects for adequacy/quality of training questions, start these questions with the sentence, “Think back during your time in <NAME OF SCHOOL OR TRAINING>.”

D. DATA PROCESSING

- Goals: To be able to ascertain sample representativeness and the extent to which satisficing occurs and to reduce item nonresponse rates.
- Comments: Data processing has not yet been completed. Results from data processing will enable NETC to determine whether survey results come from a sample that is representative of the population of graduates/supervisors. Data processing results will also indicate if satisficing and/or item nonresponse occurs and on which questions.
- Recommendations: Ask CRESST to do the following (note: some recommendations are repeated from above):
 - Descriptive statistics on demographics to ascertain if sample of responders is representative of the population of interest. If the sample is representative, then the low response rate is of less concern.
 - Checks for satisficing.
 - For surveys completed on the web, analyze paradata for survey completion times, time to complete each question, and item response rates
 - Analyze supervisor responses to see if proficiency responses correspond with quality-of-training questions. If they do correlate, it would indicate that supervisors are using the proficiency rating to respond to the training question. In this case, the training questions could be removed or changed. For example, ascertaining the extent to which supervisors

had to train up the subordinate on that task would inform NETC as to whether the subordinate's level of proficiency is due to NETC training or due to the supervisor's training.

The final technical report provided to the sponsor (Kennedy & McDowell, 2019) also contains web survey design recommendations, definitions of common survey terms, and a previously used survey with comments based upon this research.

Recommendations for Further Research

Reevaluate the response rate at a suitable interval after making the changes recommended in this report.

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NPS-19-N216-A: Identifying Traits that May Lead to Unethical Decision Making and Destructive Behavior in Navy Recruiters

Researchers: Dr. Douglas Van Bossuyt, Dr. Anthony Pollman, and Mr. Joseph Sweeney

Student Participation: No students participated in this research project.

Project Summary

Recruiting for the Navy is a unique and challenging duty that requires strong ethics and sound decision-making, and the pressures inherent in the job can lead to unethical recruiting practices. Our research is designed to assist the Navy Recruiting Command (NRC) in better identifying individuals who have the propensity for poor decision making and increased risk taking. The research questions we explored were: 1) Is there an existing assessment instrument that identifies traits in recruiters associated with unethical decision-making and destructive behavior? 2) How can an assessment instrument be developed to identify in recruiters those traits associated with unethical decision-making and destructive behavior? In working to answer these questions, we conducted a survey of existing methods and strategies to detect potential unethical decision-making behaviors, and developed a pilot psychometric risk assessment instrument in an attempt to identify recruiters who may be at higher risk of unethical decision-making and behavior. The survey of literature indicated that there are no existing suitable risk assessment instruments. As a result, we developed a pilot risk assessment instrument.

Unfortunately, we were unable to administer said assessment, given delays in Institutional Review Board (IRB) and NRC approvals, and lack of access to MAX.GOV. However, through further refinement and validation, our pilot risk assessment could be used by the Navy to identify individual recruiters who have a pre-disposition for unethical decision-making.

Keywords: *decision-making, Navy recruiting, ethics, risk attitude, Domain-Specific-Risk-Taking, DOSPERT, Engineering Domain-Specific-Risk-Taking, E-DOSPERT Likert scale, Navy Recruiting Command, NRC*

Background

Navy recruiters are put in the unique position of semi-autonomous operation in the civilian community, often times removed from command structures. Due to pressures of the position and other factors, recruiters sometimes make unethical decisions that have the potential to damage the Navy. As a result, the NRC wishes to identify an effective method of identifying signs of potential unethical decision-making by recruiting staff.

Existing research in risk attitudes with regards to risk tolerance and risk aversion across personal domains is available in the Domain-Specific Risk-Taking (DOSPERT) Scale (Blais, 2006) (Weber, 2002), and the Engineering-DOSPERT (E-DOSPERT) (Van Bossuyt, 2013), the latter designed for engineers in their professional practice across several domains. Choice lottery research is another area of study that has a significant body of literature examining risk-taking behavior (Masclot, 2009). The literature on employee risk-taking behavior provides useful background information, although little guidance on how to identify propensity for risk-taking among Navy recruiters (Libby, 1977).

In order to determine if any existing instruments might be applicable or adaptable to the Navy recruiter issue, our first research question investigated existing risk assessment instruments such as DOSPERT and E-DOSPERT and related psychometric assessment instruments, decision choice lottery assessment tools, and other related risk assessment instruments. The result of exploring the first research question influenced the second research question: How an assessment instrument might be developed to identify Navy recruiters who may be at greater risk compared to their peers of making unethical decisions. The second research question culminated in the development of a pilot unethical decision-making risk assessment instrument.

Findings and Conclusions

The project team first performed a literature survey, with a starting point in the psychometric risk-taking assessment community, primarily found in the psychology literature but also in the engineering literature. The project team also examined choice lotteries which bridge between psychology, economics, business, and engineering. While several risk-taking tools are available in the literature, none were deemed appropriate for the task of examining Navy recruiters.

Given the results of the literature review, we developed a pilot psychometric assessment instrument. In order to validate the pilot psychometric assessment instrument, a sufficient sample population ($n \geq 150$) with sufficient similarities to the population of interest (Navy recruiters) is required to attain statistical significance ($p \leq 0.05$ or similar, among other indicators). A seven-point Likert scale with an eight “not applicable” option was used for psychometric-based questions.

Unfortunately, the process timeline to receive Naval Postgraduate School (NPS) IRB approval and approval from NRC to use MAX.GOV (an inter-agency website that includes the ability to run surveys that are in compliance with federal regulations) exceeded our expectations. The delay in IRB approval and delay in access to MAX.GOV has prevented the project team from proceeding with administering the pilot assessment instrument in order to validate the instrument.

However, based on our survey of existing methods and strategies for detecting potential unethical decision-making behaviors, we can provide recommendations on how to proceed with analysis once the survey has been conducted. We believe the survey questions developed as part of this research will be useful for NRC to determine if a psychometric risk survey can effectively identify the propensity for Navy recruiters to be more or less risk tolerant in ethical decision-making situations. This is in line with what previous research has found in the domains of risk-taking in the engineering professions, and in risk-taking in an individual's personal life. The research implicates that that Navy recruiters who are more likely to have risk-tolerant behaviors can be identified, and additional support and training can then be provided, in order for said recruiters to successfully complete their duties.

Recommendations for Further Research

A pilot assessment instrument may be developed from this research, and if further research is pursued, we recommend having a sample size of at least 150 respondents, and suggest having 250 respondents to achieve statistically significant results. A variety of statistical tests and factorial analysis techniques must then be employed on the raw data to determine the validity of the proposed factors/dimensions within the survey questions. Depending on the statistical results, either 1) the proposed domains of Navy recruiter risk-taking and questions are validated, 2) the proposed domains are found to be invalid and other domains are uncovered from the data which indicates further survey development is needed, or 3) no correlation is found between the domains or the questions, which indicates that a psychometric risk-taking survey approach to uncovering recruiter pre-disposition to unethical decision-making may not be possible.

Based on our experience with developing similar survey instruments, we anticipate that the domains that were initially identified will be found to not adequately describe the intrinsic domains of risk for unethical decision-making among Navy recruiters. Most likely, between one and two rounds of survey instrument revision and re-analysis with new datasets will be needed before a statistically significant survey instrument will be finalized for use by the NRC.

The NPS project team is willing to participate in capacities as allowed by funding sources after the period of performance has ended, and we are happy to review statistical results and discuss next steps from a general background perspective with the NRC. If further funding becomes available after the FY19 period of performance has ended, we can also conduct the survey, do the statistical analysis, and develop revised versions of the pilot survey instrument.

The potential utility of the research may help the Navy to better understand the relationship between different personality trait variables and unethical decision-making among recruiters. Such individuals may then be assigned additional proactive training and closer supervision throughout their recruiting missions, in order to help them remain ethical in their decisions and actions. The success of this research may lead to a stronger, more ethical recruiting process for the Navy which in turn, may provide benefits both within the Navy and in public perception of the Navy.

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NPS-19-N230-A: Development of Job-Relevant Distraction Task/Software for Aircrew Hypoxia Training

Researchers: LCDR Brennan Cox USN Ph.D. and Mr. Larry Greunke

Student Participation: LT John Milne USN, LCDR Brendan Blain USCG, Katie Ricker CIV, and LT David Valencia USN

Project Summary

The Naval Aviation Survival Training Program's (NASTP) newly acquired Normobaric Hypoxia Trainer (NHT) was delivered with operationally-relevant tasking for pilot trainees, but not non-pilot aircrew. Using principles of instructional system design and the systems approach to training, this study identified the knowledge, skills, and abilities (KSAs) required by Class 2/4 aircrew in the conduct of their work. Surveys were developed and administered to aircrew and aeromedical experts to identify which of these KSAs were most frequently used, of high importance, and susceptible to hypoxia. The KSAs that rated highly on all three criteria were then integrated into a set of prototype "distractor tasks" for potential use in the NHT. A usability analysis with Class 2/4 aircrew and Aviation Survival Training Center (ASTC) personnel evaluated the prototype tasks on their ease of use, relevance, and level of engagement, among other factors. Results of the prototype analysis effort identified several areas for improvement and new tasks for development (e.g., a suggestion was made and acted upon to incorporate ASTC training content questions into the aircrew tasking). This research will inform future efforts by the NASTP Integrated Product Team as they prepare the NHT for operational use.

Keywords: *Naval Aviation Survival Training Program, NASTP, Normobaric Hypoxia Training, NHT, instructional system design, usability analysis, Aviation Survival Training Center, ASTC, Modeling, Virtual Environments, and Simulation, MOVES*

Background

The NASTP is charged with training naval aircrew to recognize and respond to environmental conditions that may be disruptive to their physiological and/or psychological state, to include hypoxia.

In support of this program, each of the eight ASTCs are in the process of acquiring NHTs to replace the decommissioned low-pressure chamber. The NHT will close a critical gap in the NASTP for Class 2/4 aviators, as it is capable of simultaneously training four pilots and six aircrew members.

As delivered, the NHT uses a commercially-available flight simulator to engage pilots undergoing training. However, the NHT was not delivered with operationally-relevant tasking for non-pilot aircrew. The objective of this study was to investigate job-relevant tasking to deliver to non-cockpit aircrew undergoing hypoxia training in the NHT. Per the sponsor's guidelines, this tasking would need to engage aircrew in such a manner that their psychomotor, cognitive, and/or affective performance could be monitored and evaluated for degradation as they become hypoxic. This "distraction task" would need to be compatible with all technology and system requirements previously approved for use in the NHT (e.g., software compatible with the Windows-based tablet).

As a baseline for comparison, the original aircrew tasking in the NHT was a computerized version of the card game Solitaire. This study hypothesized that a more operationally-relevant set of tasks could be incorporated into the NHT as a replacement for the Solitaire game.

Findings and Conclusions

Student investigators conducted a front-end analysis that identified 61 KSAs required by Class 2/4 aircrew in the conduct of their work. Based on these KSAs, separate surveys were developed and administered to aircrew and aeromedical experts. For the aircrew survey, respondents rated the frequency and importance of each KSA; for the aeromedical survey, respondents rated the degree to which each KSA is susceptible to hypoxia. Analyses identified 15 primary and 30 secondary KSAs from the combined data sets. Primary KSAs were those that rated highly in all three criteria (i.e., frequency, importance, and susceptibility to hypoxia) while secondary KSAs rated highly in two of the three criteria.

Student investigators evaluated all primary and secondary KSAs against seven computerized tests of cognitive abilities and psychomotor performance. This evaluation determined that no single existing test battery would provide sufficient representative tasking of the KSAs; therefore, the determination was made to develop novel tasks for capturing the KSAs relevant to the Class 2/4 aircrew population.

In collaboration with the Naval Postgraduate School Modeling, Virtual Environments, and Simulation (MOVES) Institute, all primary and most secondary KSAs were integrated into a set of prototypical "distractor tasks." Each of these timed tasks uses the touchscreen feature of the NHT tablet device and requires some level of decision-making and response. Examples include the color vision math exercise, which presents a series of simple math problems in which the equations are embedded in an Ishihara-style color blindness chart (thereby requiring visual color discrimination, number facility, and time management KSAs), and the aircraft situation awareness exercise, which requires users to identify which among a series of towers a moving aircraft's sensors is targeting (thereby requiring spatial orientation, judgment and decision making, and perceptual speed KSAs, among others).

All prototype tasks were developed in an iterative fashion with feedback from representative end users, consisting of Class 2/4 aircrew and ASTC personnel. This was achieved through multiple prototype demonstrations, administration of a formal usability survey, and informal stakeholder discussions.

Student investigators developed the usability survey, which included rating scale and open-ended items on ease of use, readability, functionality, clarity of instructions, task engagement, aviation relevance, applicability to Class 2/4 job duties, susceptibility to hypoxia, recommendations for elements to maintain in future iterations, and recommendations for elements to discard or change. Informally, end users were also asked whether the prototype tasks were a preferred solution over the baseline Solitaire tasking.

Results of the prototype analysis effort identified several areas for improvement and new tasks for development (e.g., a suggestion was made and acted upon to incorporate ASTC training content questions into the aircrew tasking). Overall, overwhelming evidence was obtained in support of the prototypes being superior to the Solitaire game for engaging non-pilot Class 2/4 aircrew during NHT hypoxia training, thereby supporting the primary study hypothesis and objective.

This study directly addressed the Topic Sponsor's command requirements by systematically identifying operationally-relevant tasks capable of replicating the psychomotor, cognitive, and affective loads of flying Class 2/4 aircraft, determining the requirements for replicating these experiences in the NHT environment, and incorporating them into a software suite capable of being used to distract non-pilot aircrew as they undergo hypoxia training. The effectiveness of the investigation team's efforts was verified through iterative testing, stakeholder participation, and feedback, with the newly developed distractor tasks receiving unanimous support as a preferred methodology over existing practices. The resulting knowledge product provides methods, analytic procedures, and results for how the job tasks and KSAs were identified and evaluated, the process by which existing tests were considered for potential use, and a description of the distractor task development and evaluation process. The software suite developed and maintained by MOVES is fully compatible with the hardware and technology configurations of the NHT. These results will transition to the NASTP Integrated Product Team as they prepare the NHT for operational use.

Recommendations for Further Research

Future research should be conducted on the availability of commercial tests that might address the KSAs identified in the early phases of this study. Operational testing should also be performed to assess objective performance on the distractor task under hypoxic and non-hypoxic conditions to determine whether and to what extent performance is affected across time and exposure. Investigations should also be conducted to evaluate the utility of synchronizing the aircrew stations such that real-time communication and task coordination can be achieved between and among trainees in the NHT; this could involve not only aircrew-to-aircrew, but also aircrew-to-pilot coordination. However, the practical benefits of this synchronization should be considered against the costs of implementing such practices, as well as the degree to which it affects overall training objectives. Finally, longitudinal research should evaluate how effectively training procedures transfer to operational behaviors, as well as how long the information is retained.

NPS-19-N246-A: Social Network Analysis and High Velocity Learning

Researchers: Dr. Gail Thomas, Ms. Sally Baho, Ms. Kimberlie Stephens, Ms. Jessica Neff, and Mr. Frank Wood

Student Participation: No students participated in this research project.

Project Summary

Findings show that the US Navy's information sharing is largely stove piped, with limited lateral information exchange occurring within individual commands or across the domain. Bottlenecks impede communication, innovation and problem solving because of a strong reliance on vertical communication problem solving and a dependence on headquarters to integrate across the commands. Social network analysis (SNA) is an analytic tool that can capture how people work together in an organization. The team assessment data corroborated the SNA findings. We concluded that while the Navy has been an award-winning organization, emerging global threats will create an increasing gap in their ability meet their mission. We suggest that commands such as these use network analysis and high performing teams (HPT) measures to optimize information flow and team effectiveness

Keywords: *social network analysis, SNA, high performing teams, HPT, organizational design*

Background

The US Navy is undergoing a large-scale organizational transformation to address new adversarial threats (i.e. Great Power Competition). To address this challenge, the Navy recognizes the need to shift how work gets done. The transformation aims to be more team-based, flexible, and agile, where rapid learning is the norm rather than the exception. These imperatives will require the redefinition of command and control, and focus on removing silos, distributing decision making, improving organizational learning and feedback, developing high-performing teams, and enhancing and enabling formal and informal information sharing, both horizontally and vertically.

SNA can be used to map information exchange in the organization, identify key nodes in the network, identify internal and external boundary spanners, and discover organizational bottlenecks. Likewise, HPTs have become central to organizations that look to address competitive forces by ensuring information flows up, down and laterally within an organization in the form of critical feedback. The move toward more team-based designs often contradicts the military's long-standing interpretation of hierarchical command and control, whether in operations or in the organizational enterprises. A reimagined view of this legacy hierarchical design is described in General McCrystal's recent book, *Team of Teams*.

Findings and Conclusions

The study addressed two primary research questions:

1. Using social network analysis, how is information flowing vertically and horizontally within and across the organizations?
2. Using a high performing team assessment, how effective are the team dynamics in these organizations?

We conducted 43 interviews across the domain including leadership teams, course instructors, and a limited number of customers. Sixty-seven leadership team members were asked to complete the team assessment and network analysis; response rate was 57% and 49% respectively. Vertical course network analysis was completed by 22/44 instructors and course supervisors, with a 50% response rate. The qualitative data was analyzed, and themes were created.

This quote encapsulated our qualitative interviews and corroborated the quantitative findings: “We do well with what we can control, but it feels like we are sustaining a sinking ship. We need to produce up-to-date training that is relevant, but our facilities and systems are failing, and we can’t update training materials when they need it.” This observation suggests the importance of re-evaluating the way work gets done.

Network analysis showed that day-to-day connectivity is relatively low across the whole network (network density 3.4%; average # of links to others 6.3, total ties 1160). Likewise, day-to-day connectivity within sites varies from low to moderate: Organization A 24.5% network density; Org B and C 10%; Org D 815%, and Org E 7.6%. Average number of links 5.4 for Org A; 4.2 for Org B; 5.0 for Org C; 1.3 for Org D; and 2.2 for Org E.

Day-to-day communication is more likely to move vertically within sites or across sites than horizontally (homophily measure 0.28). When instructors run into problems, they go up the chain. Last, the connection to the deck plate was very sparse, even at lower levels of the organization.

We found an almost exclusive reliance on headquarters (HQ) to connect the sites to one another. Without HQ as an integrator, there is sparse communication across the sites and typically only at the highest levels. Such a reliance on individuals at HQ can create bottlenecks (reducing speed of information flow) and disconnects (if individuals fail to pass along relevant information). Most people tend to ask internal people whether they are meeting the needs of external customers. A wide variety of levels, but a small number of individuals are acting as brokers of information regarding external customer needs.

In summary, the network analysis indicates that 1) vertical communication (up/down) is much more common than horizontal coordination communication, 2) a few key roles at HQ are relied upon to share ideas across the domain, and 3) central innovation brokers are not well connected in the day-to-day network.

In conjunction with the network analysis, participants rated the effectiveness of their team dynamics. The team assessment instrument and interviews measured command leadership performance against HPT standards for team effectiveness. In general, findings show that team members exchange information within their teams, but they do not adequately ‘take each other into account’ in the work that they do. This finding confirms the silo nature of information sharing found in the network analysis. Of note, the tendency for these teams to operate using a “command and control” style may impede their ability to work as high-performance teams. That is, team members may not see the need to take each other into account because they see coordinating across the organization divisions, resolving conflicts and making decisions affecting the whole organization as the responsibility of the commanding officer and executive officer, not the team members themselves.

We concluded that this domain has been considered effective based on past measures of success. In fact, in 2018 they received top ratings in NETC's excellence award. But, as the US Navy transforms to address global threats, several barriers exist that will prohibit this organization from realizing the imperatives of agility, innovation, speed, and high performing teams that would enable them to achieve the optimal performance required to compete and win in future military operations.

Recommendations for Further Research

This study was conducted to demonstrate the use of social network analysis for organizational design issues within the US Navy. Further research is needed to show how this method would be scalable, for example, private sector organizations are using organizational network plugins to improve information flow, maximize their use of talent, and evaluate various functional roles.

NPS-19-N322-A: Enlisted Detailing Market Place Analysis and Pilot

Researchers: Dr. Kenneth Doerr, Dr. James Fan, Dr. William Gates, and Ms. Nona Jones

Student Participation: LCDR Stephen Cole ADF, LCDR Benjamin Petrisin USN, LCDR Geoffrey Johnson USN, Capt Teresa Doskey USAF, and Capt Stacylee Johnson USAF

Project Summary

The Naval Postgraduate School has conducted extensive research on the enlisted assignment and retention processes within the Navy and across the other services. Research in 2018 updated earlier work on the enlisted assignment and retention processes, including two-sided matching, optimization and the Navy's current auction-based Assignment Incentive Pay program, and developed market-based courses of action (COAs). Implementing these COAs requires collecting, consolidating, mining, and protecting the data needed to implement the detailing marketplace, potentially leveraging machine learning (ML) platforms against manpower data sets, and encoding sailor record data using "blockchain" structure.

The command's value will likely be algorithm-driven, and based on billet requirements compared to sailor training records, performance data, and demographic data. This research effort will examine algorithmic approaches to combining diverse data elements into a single metric by which commands can rank sailors. In addition, to reduce the total cost of voluntarily placing the right sailor in the right billet, this research will examine how concepts from behavioral economics might nudge sailors to accept hard to fill billets, including offering personalized combinations of non-monetary incentives.

Our research shows the following: ML algorithms can predict future outcomes by finding statistical patterns in the data unobservable to humans, and help develop a fitness score for each worker-job pair; blockchain technology can provide a secure, reliable, and efficient way to distribute sensitive data, while controlling whom, where, when, and how the data are accessed; the multiple-criteria decision-making literature contains dozens of methods to aggregate individual performance and billet data to rank equivalent classes of sailors for billet-fitness, but none of these methods are well validated; and behavioral economics and non-monetary incentives can nudge sailors to accept hard-to-fill billets

Keywords: *enlisted detailing, enlisted assignment, retention marketplace, market-based compensation*

Background

The Navy needs a market-based process that is capable of meeting the Navy's job, career, and quality needs, while also meeting the desires, preferences, and aspirations of individual sailors. A more market-based process would provide flexible incentives and negotiation between sailors and commands, while creating a more voluntary system. Specifically, sailor/command negotiation in the marketplace would provide more opportunities for sailors and commands to directly or indirectly work out terms and conditions for billet assignments and enlistment contracts. It is crucial to provide flexible incentives so that commands and sailors can negotiate a wide range of monetary and non-monetary incentives as part of the assignment "package" to ensure the most qualified sailors fill all jobs.

The FY2018 research proposed alternative COAs to introduce market-based mechanisms into the enlisted assignment and retention process, specifically auctions, two-sided matching, and two-sided matching with money. Auctions are best suited to address retention issues, and the basic auction can be modified to incorporate adjustments for quality sailor performance, individualized non-monetary incentives, or both. However, auctions cannot effectively address the one-to-one assignment process required in the enlisted detailing marketplace.

In addition, two-sided matching is specifically designed to address the assignment problem, but it does not address retention or ensure that all billets will be filled, particularly hard-to-fill priority billets. However, two-sided matching with money addresses both assignment and retention problems, and therefore best fits Navy requirements for an enlisted detailing marketplace.

Findings and Conclusions

Our current research shows that the Navy's enlisted assignment and retention market process can be improved by using a combination of ML, blockchain technology, multi-criteria decision-making methods, and behavioral economics. ML algorithms predict future outcomes by finding statistical patterns in the data unobservable to humans. In a detailing market with sailors effectively bidding for jobs and commands choosing whether or not to accept them, ML can help develop a fitness score for each worker-job pair, allowing sailors and commands to more correctly rank-order jobs based on the job fit for both. Blockchain technology provides the necessary security to protect sensitive personal information with a decentralized system. Network administrators using blockchain to support a private, permissioned, and authority drive architecture, can control who, where, when, and how the blockchain is accessed, without a third-party verification system.

Additionally, current qualification and certification data can be used in combination with simple, non-compensatory multi-criteria decision-making methods to rank sailors into equivalence classes. However, the relationship between qualification and certification data and performance is not strong enough at this point, nor are those data sufficiently fine grained, to accomplish individual sailor ranking, but assignment algorithms can be built to develop the equivalence-class rankings. The Navy should choose among multi-criteria decision-making methods with smaller data requirements. For example, Technique for Order of Preference by Similarity to Ideal Solution and Complex Proportional Assessment of Alternatives appear to be good candidates. There are also several well-validated individual difference variables that predict performance, and those can be aggregated with billet data to rank individual sailor-billet fitness (e.g., Armed Services Vocational Aptitude Battery scores available from recruitment data).

Behavioral economics can also help nudge sailors to accept hard-to-fill billets (e.g., informing sailors about their fit for open billets should help correlate command and sailor preferences, improving the assignment across all COAs). Furthermore, individualized packages of non-monetary incentives can induce sailors to volunteer for hard-to-fill billets.

Recommendations for Further Research

Our research results can be extended in several ways. For example, comparing ML output versus traditional modeling, possibly targeting a specific career field, would determine correlation or disparity between the two modeling approaches. This would identify the value of ML beyond or in complementing traditional models. It would also be beneficial to conduct a cost-benefit analysis to determine if blockchain benefits outweigh the high expected implementation costs, and determine the best approach to creating the blockchain architecture: developed in house, outsourced to a defense department agency, or outsourced to a commercial provider. Further, ratio-scaled individual difference performance predictors exist and can be used by the Navy to rank individual sailors; the two best-validated measures, general intelligence and conscientiousness, should be available to the Navy from the recruitment process. Therefore, the Navy should verify the availability of ratio-scaled predictors, and then evaluate multi-criteria decision analysis methods, as currently, none are well-validated. Based on very limited evidence, Technique for Order of Preference by Similarity to Ideal Solution and Complex Proportional Assessment of Alternatives appear promising. Lastly, future research could involve a survey of commercial behavioral economics approaches to employee retention and job assignment applications. This data could help integrate additional behavioral economics approaches into the Navy's marketplace detailing model, including integrating monetary and non-monetary incentives, which would then reduce forced billet assignments.

N2/N6 - INFORMATION WARFARE

NPS-19-N017-A: Enhancing Endurance for High-Altitude UxS

Researchers: Dr. I. Michael Ross and Dr. Harleigh Marsh

Student Participation: No students participated in this research project.

Project Summary

Unmanned aerial vehicle (UAVs) are customarily flown in circles or other simple geometric shapes to achieve persistence. The results of this study indicate that enhanced endurance can be achieved by exploiting the nonlinearities of a UAV and/or the effects of the environment. The endurance enhancement is obtained by following a dynamic flight path, as opposed to operating in steady state; depending on the configuration of the flight vehicle, fuel requirements can be reduced by as much as 35%. Since the ideal flight trajectory for persistent flight deviates from easily recognizable geometric shapes like circles or figure eights, an added benefit of persistent flight paths appears to be a reduction in observability to an adversary.

Keywords: *intelligence, surveillance and reconnaissance, endurance, persistence, minimum fuel, trajectory optics*

Background

Long endurance is essential for high-altitude persistent intelligence, surveillance and reconnaissance systems. High endurance is usually achieved by means of system design and/or through the use of lightweight hardware. Regardless of the type of unmanned system used, nearly all systems use static or semi-static means to achieve persistence. For instance, for an UAV, it is customary to fly in standard geometric shapes (circle, figure 8, etc.) to achieve persistence. These flight profiles are used because they are the same as those employed in human-piloted flight. UAVs, however, are autonomous vehicles and their operation need not conform to the intuition of human experience in the cockpit. This study aims to investigate alternative flight patterns for higher-endurance autonomous flight.

A three degree-of-freedom model of a generic UAV was developed for this study. Steady-state analysis was performed using this model to determine expected fuel consumption for loitering using conventional flight paths. The ideal steady-state loitering velocity was determined by finding the trade between airspeed and fuel rate. This analysis provided the baseline fuel requirements for persistent flight.

Findings and Conclusions

A periodic trajectory optimization problem based on the three degree-of-freedom UAV model was developed to find minimum fuel loitering solutions that are more efficient than steady-state flight. Optimized solutions leverage the non-linearities of flight and/or the flight environment (e.g., wind conditions, thermals etc.) to reduce fuel requirements as compared to steady-state solutions. It was found that the flight profile for minimum fuel loitering involves two phases: the first phase is a boost phase in which energy is added using the air vehicle's engine, and the second phase is a glide phase, where the engine is throttled back to conserve fuel. The ratio of boost to glide duration depends on the footprint of the loiter pattern. Various aircraft configurations were explored, and it was found that in some cases it is possible to reduce fuel requirements by approximately 35%.

Recommendations for Further Research

The results of this study showed that endurance can be enhanced by replacing conventional steady-state flight paths with nonlinear flight paths optimized for the specific details of a UAV, in order to reduce fuel requirements. A generic UAV system was studied, therefore, future research should focus on higher fidelity modeling for specific vehicles of interest to the DoD, to best evaluate the achievable endurance enhancement for these specific systems.

NPS-19-N019-B: Advanced Concepts and Applications for Predictive Analytics in the Maritime Domain

Researchers: Ms. Bonnie Johnson and Mr. John Green

Student Participation: Mr. Jonas Brown CIV, LT Geoff Grooms USN, and CPT Scott Wood USMC

Project Summary

Naval tactical operations could take a significant leap in progress with the aid of a real-time automated predictive analytics (PA) capability that provides predictions of second- and third-order effects of possible tactical courses of action (COA). This study developed a framework and conceptual design for a real-time automated PA capability for the naval tactical maritime domain, and explored artificial intelligence (AI) and game theoretic methods that can be leveraged for this future capability. This future capability can accompany current developments in the use of AI and data analytics, to improve battlespace knowledge and offer automated battle management aids (BMA) to the tactical warfighter. As the automated BMA develop tactical COA options, the PA capability could predict how the adversary might respond to each COA option. The PA capability could continue to “wargame” possible blue force/red force actions and responses—generating predictions of second- and third-order effects. These predictions offer the tactical warfighter a more strategic perspective in making tactical COA decisions. Performing this analysis using an automated aid with AI and game theoretic methods, allows the capability to support real-time decisions, to analyze great amounts of data (both sensor data and historical data), and handle highly complex tactical environments. This real-time wargaming translates into high-order computations that couldn’t be performed manually in the short reaction times given.

Keywords: *predictive analytics, courses of action, decision aids, artificial intelligence, game theory*

Background

PA is a type of advanced analytics used to make predictions about unknown future events, and is based on a variety of analytic methods including data mining, statistics, modeling, machine learning, and AI to analyze current data to make predictions about the future (Goodfellow, Bengio, & Courville, 2016). These types of forecasting methods are being widely applied in the business domain, including those that inform marketing decisions by predicting consumer habits (Siegel, 2016), and optimize logistics inventories by predicting supply chain needs (Waller & Fawcett, 2013).

Predictive modeling uses mathematical and computational methods to predict an event or outcome (Kuhn & Johnson, 2013). These models forecast an outcome at some future state or time based on changes to the model inputs. Machine learning approaches can be used to train the models iteratively, based on data sets with known outcomes. Prescriptive analytics are a type of advanced analytics that use predictive models to suggest actions to take for optimal outcomes, by relying on optimization and rules-based techniques for decision-making.

The use of PA and prescriptive analytics can address complex decisions involving many variables and alternatives. The addition of game theory, the study of mathematical models of strategic interaction between rational decision-makers, provides a framework for studying second- and third-order effects of decisions. Game theory is an umbrella term for the science of logical decision-making for describing,

predicting, and explaining behavior. Combining game theory with predictive and prescriptive analytic methods could enable a real-time decision-making capability for developing COA options, and predictions of their outcomes and effectiveness as well as predicted effects and responses (Johnson, 2019).

Findings and Conclusions

This study developed a conceptual PA framework based on the needs of tactical warfighters, and in the context of supporting an automated battle management aid to generate tactical COAs. The objective of the PA capability is to analyze real-time tactical COA options in terms of the predicted 1st, 2nd, and 3rd order effects. AI and game theoretic methods can be incorporated into an automated PA capability to generate the many different permutations of these effects, and to evaluate them in order to identify undesired effects, and then eliminate the original COAs that might produce these effects. This study evaluated AI and game theoretic methods to study their potential application to the conceptual tactical PA capability and map them to the PA functions. The findings of the study include the high-level conceptual framework of the PA functionality and the evaluation of applicable AI and game theoretic methods. The detailed results are contained in Johnson's paper (2020), "Predictive Analytics in the Naval Maritime Domain."

Several Naval Postgraduate School students supported this research project. Jonas Brown studied concepts and architectures for gathering tactical readiness data from operational naval systems (Brown, 2019). His study provides a concept for collecting health, status, and capability information from naval systems that is crucial knowledge for the future PA capability. Geoff Grooms studies AI methods to support future battle management decision aids (Grooms, 2019). He identified machine learning methods for supporting automated tactical decision-making. Scott Wood studied the use of AI methods for combat identification, and more specifically for identifying unknown-unknowns in the tactical battlespace (Wood, 2019).

The types of AI and game theoretic methods that were identified as applicable to the future PA capability included (Johnson, 2020): statistical methods (such as regression analysis and discriminant analysis), graph theory methods (such as a Bayesian network), learning methods (such as supervised and unsupervised machine learning), and game theoretic methods (such as descriptive and normative interpretation, regret minimization, and counterfactuals).

Recommendations for Further Research

In conclusion, contributions from many fields of AI and game theory will be welcomed to meet key challenges and realize new opportunities for developing a PA capability to support naval maritime operations. This study identifies a number of AI and game theoretic methods that could be applied to further develop a PA capability to support future naval tactical decision aids.

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NPS-19-N036-A: CYBER/RF MILDEC in Naval Operations / NPS-19-M185-A: Optimized Network Emulation of Signals Intelligence (SIGINT) and Tactical Cyberspace Environments for MAGTF Training

Researchers: Dr. Randy Maule, Mr. Christian Fitzpatrick, and Dr. Imre Balogh

Student Participation: No students participated in this research project.

Project Summary

The models, workflows, and instrumentation in this research present operational methods, and the analytics provide status for command decision support. Specifically, implementation addresses tactical clouds, data science for real-time assessment, and artificial intelligence (AI) for predictive analytics. In turn, sensors assess the radio spectrum, agents measure network traffic, and data science provides visualizations with detailed analysis, while machine learning and AI support execution automation.

Keywords: *cyber, radio frequency, RF, military deception, MILDEC, signals intelligence, SIGINT, training*

Background

The Department of Defense has been creating new infrastructure to organize cyber and electronic warfare, however, the technologies are not fully realized to manage these new capabilities in terms of infrastructure and specialized warfighter skills. Research is needed to define infrastructure for tactical radio frequency (RF)-to-cyber and design warfighter training for operational implementation, and is advanced through four objectives in two use-cases.

Findings and Conclusions

In this work, training techniques and technologies for cyber/RF military deception were investigated, and scenarios for distributed cyber/RF operations were designed. Signals in the RF physical environment included: Wi-Fi, commercial cellular, ultra-high frequency, very high frequency, and satellite communications. Additionally, nodes were emulated for tactical communications with state and non-state actors, and command operations were evaluated in a congested signals intelligence and cyberspace environment.

Recommendations for Further Research

Future research may extend our models, methods and instruments in specific operational scenarios, and develop the database to automate execution. Additionally, AI and machine learning capabilities may be extended, and training for specific scenarios based on defined operational contexts can be designed and developed.

NPS-19-N051-A: Improving Tactical Environmental Support in Data Denied Areas: Applications of Machine Learning (ML)

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Student Participation: LCDR Kellen Jones USN, 2d Lt Darby Maier USAF, 2d Lt Jacob Lang USAF, Ms. Sooyeon Kim CIV INT, Ms. Anjali Golechha CIV INT, and Mr. Paulo Jauregui CIV INT

Project Summary

Battlespace decisions rely on accurate environmental predictions on both long and short timescales to optimize operational success of missions. Post-processing of numerical model forecasts, using a machine learning algorithm, has been shown to reduce environmental prediction error. In this study, tests were done to determine the length and type of learning data needed to improve forecasts of low-level marine stratus clouds and near-surface winds. Climate analysis was also done using known climate predictors to select analog periods to define learning data. Results show improvement of short-term cloud and wind forecasts with learning periods of five days or less, making the algorithm applicable to data denied regions.

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

Background

Errors in forecasts of environmental conditions can have substantial negative impacts on national security operations. Forecasts of environmental conditions for long-range mission planning and short-range mission execution are generally provided by dynamically based numerical models. The magnitude of numerical model forecast error varies considerably in space and time, which makes them hard to anticipate and correct. This is especially true in data denied areas where there are little, if any, observations to assess error and correct forecasts.

Techniques to mitigate these deficiencies in numerical weather prediction (NWP) model forecasts, through post-processing of model data, have proven useful. The model output statistics (MOS) approach (Glahn & Lowry, 1972) uses multivariate linear regression techniques to make point forecasts of sensible weather from NWP output. This approach requires relatively large amounts of observations and model forecasts to develop the regression equations. Contemporary post-processing research by Gneiting (2014) implemented a univariate non-homogeneous regression approach to ensemble model output statistics. Richter (2012) added a Bayesian approach to ensemble model output statistics for a single variable. Wendt (2017) extended this Bayesian approach to a full multivariate approach, using a hierarchical parameter structure, and showed that even with limited learning data, this approach can significantly reduce error. Critical to the application of these post-processing approaches is a sufficient set of learning data, consisting of both observations and model forecasts. The performance of the Naval Postgraduate School's Bayesian ensemble model output statistics (BEMOS) post-processing showed nearly equal skill for 30-day and 1-year learning periods (Wendt, 2017), especially when similar weather patterns were used in the training. To optimize model learning to extend this application to data denied regions, longer-range, large-scale variations due to climate conditions may help identify analog periods to use as learning data in the BEMOS post-processing. The success of this approach depends on being able to identify appropriate climate patterns in advance. The BEMOS model can also be applied to this climate prediction problem to identify particular large-scale weather patterns.

The objectives of this study are to test the application of the BEMOS post-processing model to various short-range forecast problems, as well as to determine its applicability to identify climate patterns in past data. Specifically, the impact of time and spatially limited learning data on forecast error is examined. Furthermore, the ability to identify and predict high-impact climate patterns using the BEMOS model is evaluated.

Findings and Conclusions

This study examines the utility of using a machine learning technique to post-process numerical predictions of environmental variables to reduce error, as well as identify impactful climate regimes to improve environmental support. We have conducted a series of tests to determine how well this approach can be applied in data denied areas that are of operational interest. Specifically, short-range low-level cloud and surface wind forecasts as well as long-range climate pattern forecasts have been examined.

To test the application of the BEMOS machine learning to long-range, large-scale prediction of high-impact weather, the problem of Santa Ana offshore winds was used. A characteristic long-wave pattern that is associated with Santa Ana wind events was identified using climate analyses. Results using the Madden-Julian oscillation phase as a predictor showed strong predictive skill for the Santa Ana long-wave pattern that extended to as much as 21–28 days of lead time. These results indicate that the machine learning algorithm can potentially select climate patterns to use in training short-term forecasts within the particular climate pattern.

Direct model forecasts of both clouds and surface winds exhibit considerable errors that have large operational impacts when incorrectly forecast. Numerical model forecasts of marine stratus cloud forecasts often fail to depict actual cloud cover for time periods even as short as 3–6 hours. The machine learning algorithm was applied to 1 km resolution model forecasts using cloud water, relative humidity, surface elevation, and vertical motion as predictors.

These predictors were then trained against 1 km visible imagery as verification for training periods of one to three days. Results showed that forecast details about the location and timing of the clearing of existing clouds were generally improved through the machine learning. However, the machine learning failed to adequately generate clouds when conditions were already clear and the predictor variables contained no clouds.

Numerical model wind forecast error is often rather large in coastal regions where complex topography and coastline geometry impact the underlying dynamics. To correct these forecasts, the statistical model was run using three predictors (wind speed, direction, and surface pressure) for the Monterey Bay region and calibrated using surface observations. Learning periods ranging from three hours to seven days were examined. In addition, data from the same time each day were compared to data from multiple times per day to use in the learning. Results showed that five days, using the same time of day, produced the best forecast improvement. Wind speed errors generally decreased by 0.5–1.5 m/s with the largest reduction occurring for the higher wind times of day, which represents a 15–25% improvement in the absolute wind speed forecast.

Recommendations for Further Research

The results from the study indicate that improvements in cloud and wind speed forecasts can be achieved by applying a machine learning approach to correct for typical forecast errors. This study was limited to tests in the Monterey Bay region for a small sample of forecasts. Determining the forecast improvement over a broad range of weather forecast events should be examined. In addition, coupling the climate prediction of analogous weather patterns to define similar learning data periods needs to be tested and compared to other learning periods such as most recent 5–7 days. Finally, the probability distribution produced by the BEMOS algorithm should be extracted to help decision makers utilize the forecasts most effectively.

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NPS-19-N072-A: Network Classification with Incomplete Information

Researcher: Dr. Ruriko Yoshida

Student Participation: LT Carolyn Vu USN, and LT Ross Spinelli USN

Project Summary

With the growth of accessible data, particularly for incomplete networks, a demand for effective methods of analyzing networks has emerged. Even as means for data collection advance, incomplete information remains a reality for numerous reasons. For example, data can be obscured by excessive noise, and surveys for information typically contain some non-respondents. In other cases, simple inaccessibility restricts observation. Also, for illicit groups, we are confronted with attempts to conceal important elements or propagation of false information. In the real-world, it is difficult to determine when the observed network is both accurate and complete.

In this research, we consider two objectives: (1) a method for classification of incomplete networks (network classification) and (2) inference on how much missing information (network completion problem). In contrast to the current method of training models with only complete information, we examine the effects of training our classification model, and training network completion problem, with both complete and incomplete network information.

Our results strongly indicate the need to include incomplete network representations in training the classification model and network completion. Incorporating incomplete networks at various stages of completeness allow 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. We also confirm these simple, easily calculated network features are sufficient to classify an incomplete network and network completion.

Keywords: *machine learning, network classifications, network completion problem, random forests*

Background

An intelligence community's assessment of enemy organizations requires accurate classification of the observed network before the intelligence team can develop a strategy for combating the adversary. Problems are typically time-sensitive; however, gathering this complete and actionable intelligence is a challenging mission that could span years. An adversary's actions are secretive in nature, making it extremely difficult to collect a complete observation of the network. Crucial information is deliberately concealed. Intentionally dubious information might create problematic noise or false imputations. Thus, if an observed incomplete network can be classified as-is without delay, the network can be properly analyzed for a strategy to be devised and acted upon earlier.

With a method to accurately classify an incomplete network, techniques of imputation can be reserved for post-classification. This allows for the estimation to be tailored accordingly by network class in an effort to maintain the network's true structure. These techniques could provide the intelligence team with a reasonable evaluation of an enemy's prospective associations or activities. It is commonly understood that graphs of a class will have similar characteristics in its topology.

Under this assumption, unique network features should be leveraged to classify an unknown network. Li et al., (2012) proposed an alternative approach to kernel methods, and conducted a study of biological network classification based on attribute vectors generated from global topological and label features. They discovered that networks from similar classes have similar characteristics, and network characteristics carry distinctions leverageable in classification algorithms. This study found their feature-based classification models produced similar accuracy rates, with less computational requirements, than conventional kernel methods of measuring similarity between networks based on shared patterns.

Canning et al., (2018) investigated the use of network features for classification of real-world observed networks. Their research found that networks from differing classes do contain distinguishing structural features useful in network classification. Research prior to this study was mainly focused on classification of synthetic networks or different networks within one specific class. Their study included synthetically generated networks, and Canning et al., (2018) discovered “synthetic graphs are trivial to classify, as the classification model can predict with near-certainty the network model used to generate it.” Their multiclass classification model using random forest (RF) was successful in classifying real-world networks using network features.

All of the aforementioned studies of feature-based classification presume complete network information in their methods. In contrast, we seek to examine an RF model that classifies a graph as it is observed—even while incomplete. Incomplete data is a reality of analyzing real-world networks as portions of the observed data may remain unknown for different reasons, such as: data obstruction by excessive noise, non-respondent survey answers, deliberate concealment, or inaccessibility for observation. The proper handling of incomplete data is a critical requirement for accurate classification, and an inapt approach could cause significant errors in classification results.

Our approach for handling incomplete data is the use of machine learning (ML) techniques, such as support vector machines and decision trees. However, when using any of these methods, we must be attentive to potential incidents of significant bias, added variance, or risks of generalizing estimated data. Thus, we seek to develop a method for classifying an incomplete network without estimations to complete the network. Once classified, the methods of predicting unknown data can be customized to consider that network class’s known properties, not just its observed features.

Findings and Conclusions

In this research, we consider a method for classification of incomplete networks. We examine the effects of training the classification model with complete and incomplete information. Observed network data and their network features are classified into technological, social, information, and biological categories using supervised learning methods. This comparative analysis contributes to a better understanding of network characteristics for classification. Then we consider to create a robust method for rebuilding a graph network with missing information. We propose a method for classifying the percent of information missing in networks based on feature characteristics, which will determine how much information needs to be rebuilt. In this project two students, LT Carolyne Vu and LT Ross Spinelli participated. LT Vu worked on the classification of network from an incomplete network, and LT Spinelli worked on the network completion.

First, we consider a method for classification of incomplete networks, and classify real-world networks into technological, social, information, and biological categories by their structural features using

supervised learning techniques. In contrast to the current method of training models with only complete information, we examine the effects of training our classification model with both complete and incomplete network information. This technique enables our model to learn how to recognize and classify other incomplete networks. The full results are reported in LT Vu's thesis (Vu, 2019).

The representation of incomplete networks at various stages of completeness allows the machine to examine the nuances of incomplete networks. By allowing the machine to study incomplete networks, its ability to recognize and classify other incomplete networks improves drastically. Our method requires minimal computational effort and can accomplish an efficient classification. The results strongly confirm the effectiveness of training a classification model with incomplete network information.

In LT Vu's thesis, we found that if we train machines with not only complete networks but also incomplete networks the accuracy rates increased dramatically even with real life networks. Especially that our method of training with both complete and incomplete information achieves improves classification rates at all stages of network incompleteness. The foundation established in LT Vu's work allows for an enhanced understanding of incomplete networks (Vu, 2019). Opportunities for follow-on research extend to incorporation of this classification model into practical implementation and exploration of other ML techniques. In this project, we are taking the next step. Based on LT Vu's work, we can classify what kind of the model we should consider for fitting the observed network. However, we need to know how much information the observed network is missing.

For the second part of this project, the network completion problem, the full results are reported in LT Spinelli's thesis (2020). Essentially, LT Spinelli worked on developing a novel ML model to accurately infer how much information the observed network is missing. Here, we used simulated data sets generated by the following models: (1) Erdos-Renyi (ER), random graph, nodes and probability of edge connection; (2) Barabasi-Albert (BA), Scale-free network (Follows power law), preferential node attachment; (3) Random Geometric (RG), partial network, uses radius to determine edges, and; (4) Small World (SW), similar to Erdos-Renyi, but this model is used for analyzing social networks.

Then we set up the two scenarios: (1) heterogeneous graphs: the heterogeneous graphs contain graph calculated characteristics for varying parameters of the specific graph type. For each dataset (RG, SW, BA, and ER) we change two inputs, the amount of missing information and the parameter for the specific graph; and (2) homogeneous graphs: the homogeneous graph data sets contain calculated graph characteristics for a single given set of parameters. The only changing difference between each of the graphs is the percent of data missing as the ML methods are able to perform better with less changing parameters. These graphs are simpler, and will not be required to distinguish between percent missing and a graph with varying parameters.

We ran experiments with two scenarios: (1) missing nodes and edges associate with these nodes and (2) missing only edges of a network. For both scenarios, we can accurately infer how much information is missing with more than 98% accuracy from simulation studies if we use RF and Adaboost as classifiers.

Presently, the application of this classification method is being explored for a Department of Defense Unmanned Autonomous Vehicle (UAV) network control project in a joint effort between the Operations Analysis, Mechanical and Aerospace Engineering, and Computer Science Departments at the Naval Postgraduate School.

Recommendations for Further Research

This research establishes a foundation for the continued study of incomplete networks; efforts to incorporate this classification model in real applications is necessary for testing the model's practical implementation. Future research efforts should also allow for an enhanced understanding of incomplete networks, and how to classify them, including methods of accurately classifying sub-portions of a too-large network. Also, the networks we examine are limited to static observed networks, therefore, future efforts should include dynamic networks. Additionally, while our research confirms the advantages of a standard supervised learning method in classifying incomplete networks, a deep learning approach ought to be considered to harness its capability and flexibility to process larger amounts of raw data through its incremental layered learning (LeCun et al., 2015).

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NPS-19-N155-A: Hydrodynamically-based Detection of the Surface and Subsurface Wakes

Researchers: Dr. Timour Radko and Mr. John Joseph

Student Participation: CDR David Lewis USN, LT David Kramer USN, LCDR Jack Dougherty USN, and LT Jacqueline Zimny USN

Project Summary

This study was designed to advance our understanding of the physical principles that govern the evolution of stratified wakes, providing the basis for the development of hydrodynamically-based submarine detection methods. Results from numerical and laboratory experiments performed by the principle investigators (PIs) and Naval Postgraduate School (NPS) thesis students are highly encouraging in terms of operational guidance, and include (i) estimates of the detection periods for wakes in active oceanic environments (Radko & Lewis, 2019), and (ii) exploration of the effects of internal waves generated by propagating submersibles (Danieletto et al., 2019). Promising findings indicate that hydrodynamically-based detection could influence the tactics of undersea warfare.

Keywords: *stratified wakes, non-traditional detection, undersea warfare, battlespace environment, detection and avoidance*

Background

The primary motivation for studies of stratified wakes comes from naval applications—the need to control, detect and monitor dynamic and thermodynamic signatures of moving underwater vehicles. At the same time, analysis of stratified wakes constitutes an important component of classical fluid mechanics (e.g., Lin & Pao, 1979; Radko, 2001; Spedding, 2014). Much of the work done to date is based on the laboratory (e.g., Voropayev et al., 1999, 2007; Merriam, 2015; Danieletto, 2018) and numerical experiments (e.g., de Stadler and Sarkar, 2012; Chongsiripinyo et al., 2017; Davis, 2018; Guerrero, 2018, Radko & Lorfeld, 2018; Radko & Lewis, 2019). The dynamics and modeling laboratory at NPS has made considerable inroads into the problem, particularly through thesis research of Navy students at NPS. Of particular relevance for the present proposal are our experimental results from the field programs of 2015 and 2016, which are fully consistent with modeling-based expectations. The wake produced by towing a rigid cylindrical body (Moody et al., 2017) resulted in a clearly identifiable thermal perturbation in the main thermocline.

Findings and Conclusions

Our investigation focused on the wake dynamics and detection potential in relation to the characteristics of (i) the submersible itself—its speed, depth, and size, and (ii) the ambient fluid, including thermal and haline stratification, planetary rotation and levels of background turbulence. These results will assist the Navy in the identification of detection vulnerabilities and affect the tactics of undersea warfare by narrowing the submarine search areas. The essential findings were reported in Radko and Lewis (2019) and Danieletto et al., (2019).

The research component reported in Radko and Lewis (2019), attempted to quantify the decay rates of stratified wakes in active oceanic environments, characterized by the presence of intermittent turbulence and double-diffusive convection. Of particular interest was the possibility of utilizing standard oceanographic microstructure measurements as a means of wake identification and analysis. The investigation was based on a series of direct numerical simulations of wakes produced by a sphere uniformly propagating in stratified two-component fluids. We examined and compared the evolution of wakes in fluid systems that are (i) initially quiescent, (ii) double-diffusively unstable, and (iii) contain preexisting turbulence. The overall conclusion from our study is that the measurement of microscale signatures of turbulent wakes could represent a viable method for hydrodynamic detection of propagating submersibles.

The study of Danieletto et al., (2019) was focused on drag evaluation and prediction, which are integral to maximizing the efficiency of nautical vehicles and limiting their hydrodynamic signatures. One source of drag that remains poorly understood, yet has significant effects for vessels traversing stratified waters, is the dead-water phenomenon. It represents the dramatic increase in drag associated with internal waves created by the body itself. This phenomenon has been studied in the literature for surface and submerged vessels separately, but little attention has been given to directly comparing the two. Our research investigated the dead-water effects by comparing laboratory outcomes for both submerged and surface body experiments in stratified and unstratified fluids. By comparing the drag coefficient measured in each case, we found that the stratified contribution to the drag coefficient is comparable for surface and submerged bodies.

The change in the drag coefficient caused by stratification is always positive in these experiments, but is much larger for speeds lower than the maximum phase speed of the system. This implies that the dead water modification to the drag coefficient does not depend on the location of the body, which is an important consideration in determining the depth of maximum efficiency for vessel transport.

In the course of this project, four Navy students (CRD Lewis, LCDR Dougherty, LT Kramer, LT Zimny) performed their thesis research on hydrodynamically-based detection, concurrently learning techniques of high-performance computing.

Recommendations for Further Research

Our present investigation stimulated several promising ideas for follow-up projects. These ideas are currently pursued by the thesis students supervised by the PI and Co-PI. LCDR Dougherty is performing a series of numerical simulations of submarine wakes in an active field of internal waves, and these simulations will be used to assess the prospects of satellite-based detection for a given depth and speed of a submersible. LT Kramer is exploring the ramifications of submarine maneuvering for wake detection, and LT Zimny currently works on the development and use of artificial intelligence and machine-learning techniques for the identification of late wakes.

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NPS-19-N157-A: Leveraging AI in Support of Decision Superiority – Enabling AI, a System of Systems Approach

Researchers: Ms. Bonnie Johnson, Dr. Doug MacKinnon, Mr. John Green, Dr. Ying Zhao, and Mr. Tony Kendall

Student Participation: Mr. Hugh Pollard CIV, Mr. Jonas Brown CIV, LT Geoff Grooms USN, Capt Scott Wood USMC, and Ms. Margie Palmieri CIV

Project Summary

The Navy has recognized the need for automated decision aids to support battle management as warfighters become overwhelmed with shorter decision cycles, greater amounts of data, and more technology systems to manage. To date, much emphasis has focused on data acquisition, data fusion, and data analytics for gaining situational awareness in the battle space. However, a new frontier and opportunity exists for using this data to develop decision options, and predict the consequences of military courses of action (COA). This project studied the application of artificial intelligence (AI) methods to enable and enhance future battle management aids (BMA) for naval tactical operations. The researchers used literature review, a grounded theory research methodology, and modeling and simulation to: (1) study different architectural and AI aspects of BMA, and (2) develop and validate a theory for an engineered, complex adaptive system of systems (CASoS) solution which relies on AI and distributed intelligent agents. The study results include a validated CASoS theory and conceptual design and recommendations for AI methods including machine learning (ML), deep learning (DL), data analytics, and architectural concepts for supporting naval tactical BMAs.

Keywords: *artificial intelligence, decision support, courses of action, machine learning, battle management*

Background

Tactical warfare is complex (Bar-Yam, 2004). The complexity, range, and speed of war are driving us to new technologies to remain competitive, and successful tactical operations require agile, adaptive, forward-thinking, fast-thinking, and effective decision-making. Advancing threat technology, the tempo of warfare, and the uniqueness of each battlespace situation—coupled with increased information that is often incomplete and sometimes egregious—are factors that overwhelm human decision-makers. Advances in AI methods, increased amounts of data, and improvements in computational capabilities lead to a potential solution to address this complexity—a solution combining improved tactical knowledge, automated decision aids, and predictive capabilities.

AI technology has the potential to improve warfighting decisions by prioritizing threats and operational missions, determining COA options based on distributed warfare capabilities and their expected

performance, and incorporating predictions of consequences into the decision loop. AI predictive analytic (PA) methods could form the basis of a near-real-time wargaming capability to support military tactical operations, as well as bridge the gap between the planning and tactical domains (Johnson, 2020).

There are many real-world challenges that AI technologies can address, including self-driving cars, air traffic management, finance and market analysis, telecommunications, hospitals, medical insurance, and marketing. One aspect of the tactical domain that sets it apart is the existence of the adversary whose objective is to outthink and overtake our military. This adds another dimension to the challenge of gaining situational knowledge and making effective decisions, as the adversary is intentionally attempting to obfuscate our knowledge and counter our actions. The inherent complexities in the tactical domain include: unexpected and rapidly escalating events, deadly threats of many types, a variety of missions involving defensive and offensive operations, rules and procedures dictating COA, inaccurate and incomplete knowledge of the situation, and COAs that produce a range of potential consequences and adversary reactions. AI technologies can support human decision-makers in facing such a complex decision space.

AI technologies have the potential to pay big dividends for naval tactical decision superiority (Johnson, 2019a). AI enables BMAs for improving combat identification, identifying and assessing tactical courses of action, coordinating distributed warfare resources, and incorporating predictive wargaming into tactical decisions. AI is not off-the-shelf, one size fits all, or self-contained. This study explored concepts for incorporating AI methods into decision aids to improve naval tactical knowledge and achieve decision superiority.

Findings and Conclusions

The purpose of this study was to understand how AI can be leveraged to enable naval tactical decision superiority. Specifically, the study developed conceptual designs for battle management aids that can support real-time tactical decisions by identifying COA options for distributed warfare assets. Johnson (2019b) developed a theory for an engineered Complex, Adaptive Systems of Systems (CASoS) solution approach to the Navy's highly complex tactical environment. The CASoS approach relies on a system of distributed intelligent agents that share and process data using AI and PA to develop effective COA options.

Several student thesis research studies supported this Naval Research Program project. Geoff Grooms (2019) and Scott Wood (2019) both studied AI methods. Grooms studied AI methods that can support future naval tactical BMAs. Wood studied AI methods to support the search for unknown-unknowns in the battlespace. Hugh Pollard (2019) studied the use of ML methods as an application for the Close Air Support mission. Jonas Brown (2019) developed a conceptual architecture for gathering naval tactical system diagnostic information to support force readiness knowledge and self-awareness. Margie Palmieri (2019) is currently studying data architectural patterns that can support future BMAs.

Several aspects of this research contribute to an expansion of knowledge. The CASoS theory provides new knowledge in the fields of systems science, complexity science, systems of systems, and systems engineering. The thesis projects by Grooms and Wood identify several specific AI methods that have potential value to the Navy, while Brown and Palmieri's studies provide a greater understanding of naval tactical architectural concepts for gathering and sharing self-awareness data and supporting future BMAs.

The primary finding of the project was the validation of the CASoS theory, which demonstrated a need for a set of distributed intelligent agents that use AI methods to develop and evaluate tactical COAs. The CASoS engineering framework enables the realization of future BMAs, which will lead to naval decision superiority in the tactical realm. Additional findings of this research include the identification of specific AI methods and architectural concepts that have potential application.

Recommendations for Further Research

This study identifies a number of new and interesting applications and research areas. The high-level conceptualization and systems engineering approach that derived from the CASoS theory present rich areas for further research, modeling, and development. Studying CASoS applications to complex problem domains is an immediate need with critical implications. This area of future work begins with the identification of highly complex problems, which could be addressed by a CASoS solution, including: military tactical operations (including naval tactical maritime operations, army land-based tactical operations, joint and coalition theater and area operations, littoral combat, missile defense, special forces operations, space as a military domain); future complex airspace (including commercial, personal, military, and unmanned aviation); future automated land-based transportation (with future self-driving cars and associated automation in navigation and traffic control); cyberspace (as automation and networks continue to increase presenting great vulnerabilities); and global logistics operations (military, shipping, and commercial operations involving global distribution). Future work would focus on developing conceptual designs for engineered CASoS solutions to these problem domains.

A number of interesting studies can be conducted to better understand AI applications to naval warfare. Studies can include: understanding emergent behavior as designed from a top-down perspective; studying the effects of uncertainty that can result from incomplete and inaccurate data (studying how this affects knowledge discovery, PA, and decision-making); studying the expected performance capabilities of multi-level, multi-minded constituent systems under a variety of operational scenarios; studying complex problem domains based on different operational scenarios; studying temporal effects on decision-making (how decision time affects decisions and their outcomes); studying PA methods (studying their effect on decisions and decision outcomes).

Additional studies of data analytic and AI methods could support a more detailed design of CASoS intelligent agents. Many data analytics and AI methods exist and continue to be developed. A review of these methods could identify effective capabilities and applications in support of CASoS decision-making, prediction, knowledge discovery, data management, self-awareness, situational awareness, synchronization among distributed intelligent agents, and developing confidence levels associated with knowledge and decision. Identifying these methods will support the eventual detailed design of a CASoS intelligent agent.

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NPS-19-N163-A: Big Data Meet ML and AI for Decision Superiority at the Tactical Edge – Algorithm Design, Demonstrate and Concept Model

Researchers: Dr. Ying Zhao and Dr. Dan Boger

Student Participation: No students participated in this research project.

Project Summary

This project and its previous Naval Research Program studies demonstrate a logical, incremental introduction of futuristic technologies—here, machine learning/artificial intelligence (ML/AI)—toward improving tracking, identification, and engagement doctrines. In our research this year, we developed a process of applying ML/AI algorithms (training and test) directly to a combat identification (CID) tactical decision point: 1) When a track in a CID system—i.e., the trajectory of the unknown airborne object—begins formulating, that object's observable data (e.g., kinematic features such as speed, acceleration, and altitude) are processed by the algorithm(s) at each point of the track; then 2) when the confidence of a CID classification (based on the algorithm(s)) increases, the predicted class of the object changes from unknown to known classifications.

We thus showed that the ML/AI algorithms, such as Soar-Reinforcement Learning (RL), improved the fidelity and reduced the latency of a traditional method of tracking and identifying unknown objects—the composite ID system in the CEC. Such high-confidence or high-fidelity classifications cannot be done automatically or in real-time at each track point by using traditional methods, which require a human to perform this task at a high frequency. Because the algorithms or the AI assistant can classify the object at each track point, the algorithms reduced the warfighters' cognitive burden in the CID task.

We also showed that ML/AI algorithms such as lexical link analysis (LLA) can be used to discover patterns and anomalies in the Common Tactical Air Picture (CTAP) and CID track data. The patterns can be used to identify neutral airborne objects that behave in a predictable way, and therefore reduce the big data for CID, since humans can focus resources on classifying un-neutral objects as high-priority hostile objects. Anomalies are detected that might be used as early indications for hostile intention of the underlying airborne objects. Early detection of hostile intention can save precious decision time for actions in a tactical environment, where airborne objects are plenty and decision time is very short.

We delivered an integrated demonstration of the Soar-RL CID AI Assistant to the CEC program office on August 30, 2019, replaying data from a real-life CID operational CEC exercise held in June 2018. The Soar-RL CID AI assistant demonstration showed that the system's readiness has reached the level of module and/or subsystem validation in a relevant environment. As a result, the system has been selected for further testing in the Trident Warrior 2020 exercise.

Keywords: *big data, deep analytics, machine learning, artificial intelligence, Soar-RL, Soar-reinforcement learning*

Background

CTAP is a process to collect, process, and analyze data from a vast network of sensors, platforms, and decision-makers to provide situational awareness to air warfare decision-makers. CID is a process to precisely identify critical airborne objects as friendly, hostile, or neutral. The key challenges of CTAP and CID include an extremely short timeframe for targeting, data fusion, and decision-making, a need to process heterogeneous data sources, uncertain and/or missing data outside sensor (e.g., radar, radio) ranges, and unknown, hidden information about and intent of detected objects, all combined with humans in the loop, which makes for multiple slow, manual decisions.

In particular, the heterogeneous nature of tactical data from various sources reveals non-linear relationships between data elements that are critical for high-fidelity and low-latency decision-making in CTAP and CID. The initial hypotheses were that emerging technologies such as ML/AI algorithms, including data fusion, pattern recognition, anomaly detection, machine vision, and reinforcement learning (RL) algorithms, have the potential to address these CTAP and CID challenges by leveraging state-of-the-art parallel and fast computing, and the algorithms' abilities to match a certain level of human intelligence, thereby allowing good decisions to be determined much faster and more accurately.

The work reported here is a continuation of previous studies (Zhao, 2015, 2016, 2017, 2018) that demonstrated the role of big data and deep analytics, including ML/AI, in this context. Previously, we studied the current status of the CTAP and CID problem, visiting a destroyer ship and several DoD research labs and communicating with tactical action officers, the prospective end users and ultimate stakeholders of this application, to understand how warfighters currently perform the task of CTAP and CID decision-making, what data and tools they use for decision-making, and what challenges they face. Based on this initial research, we selected and started to apply ML/AI algorithms to address the challenges.

We then focused on the Soar-RL algorithm, a cognitive architecture for modeling complex cognitive functions (Laird, 2012) that includes reinforcement learning, performing a small-scale test in a student

thesis project (Zhao, 2016).

Findings and Conclusions

These results confirm the majority of our original expectations and predictions that ML/AI algorithms have the potential to automate the CID task for warfighters in a tactical environment. Initially, we thought the CTAP/CID problem was solely a problem of interpreting big data, and we assumed that big data would always be available. This hypothesis is only partially supported by the research experience since we found that some unknown objects' behaviors are not observable: for example, adversaries usually try to hide their intentions, so no data is available. When the data is not available (i.e., unknown classes), the unsupervised machine learning methods, such as LLA, that we applied are useful to identify anomalies.

Our results will benefit Navy operations related to the CTAP and CID and contribute to command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) and decision superiority at the tactical edge. The Soar-RL CID AI assistant is the first demonstration of ML/AI application shown to the CEC program office and to a Naval annual exercise such as Trident Warrior. The resulting system will help enable the mandatory ADS-B-aided CID capability: by leveraging our research results, the ADS-B-aided CID capability will also be powered with ML/AI. This matches a fleet requirement and can be readily transitioned and help the OPNAV N2/N6 missions.

Recommendations for Further Research

Continuing to improve the technology readiness level of the Soar-RL CID AI assistant will require conducting the module and/or subsystem validation in a relevant end-to-end environment. To achieve the goal, we recommend the following actions:

1. Build the integration/interface to the other systems in the relevant end-to-end environment.
2. Test on the live-feed CID data and apply the Soar-RL CID AI assistant to the real-time live-feed data.

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NPS-19-N191-A: Joint Fires in Support of Distributed Maritime Operations

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

Student Participation: Mr. Shawn Brier CIV, Mr. Peter Bach CIV, and Ms. Lauren Mcneil CIV

Project Summary

As the Distributed Maritime Operation (DMO) concept continues to evolve, the idea of Joint Fires (JF) in support of DMO is gaining traction. This study explored options and concepts for employment of joint assets in support of maritime operations, and enabled maritime calls for fire, supported by air- and land-based assets in the degradation and denial of Red Force reef island outpost capabilities. Specifically, we explored how well a small adaptive force composed of the Army, Air Force, Navy, and Marines can synchronize and coordinate a limited strike to destroy key enemy assets, and how the utilization of the wireless mesh network affects those operations. The aim was to determine whether a mesh network will help or hinder the speed and accuracy at which the nodes can communicate. This research addressed and quantified potential benefits to mission success through the employment of a specific type of network. The mission success for this project was defined as the ability to effectively send and receive the voice, video, and data transmission necessary to support a joint fires limited strike. We suggest that further research include examination of scalable SATCOM networks to support larger user bases, possibly into the thousands.

Keywords: *joint fires, distributed maritime operations, mesh networks*

Background

The maritime domain is described by the Joint Maritime Operations as consisting of oceans, seas, bays, estuaries, islands coastal areas, and the airspace above these, including littorals. It is in this environment that this research explores, through model and simulation, the effectiveness of a mesh network and how the type of communications network can influence mission success. In an article titled, “Hiding Comms in Plain Sight,” the authors specifically mention the littoral operational environment as one being a challenge due to the physical geography and congested waterways (Bordetsky, Benson, & Hughes 2016). Operating in a crowded environment or an environment where the geography physically constrains operations adds an increased layer of complexity to the effectiveness of a network. In these types of environments, “where defensive and offensive measures are much harder to carry out” success often relies on an ability to stay mobile and flexible (Bordetsky, Benson, & Hughes 2016).

Networks that can automatically adapt to dynamic situations and still provide robust capability are critical to mission effectiveness. Mesh networks are potentially a solution to the complexity that complicates the congested maritime environment. The inherent characteristics of a mesh network allow for each node within the network to act as a router. Each node is self-aware and can create a path depending on the message type and the intended target. As a result of these self-healing and autonomous links, these “undetectable mesh networks can deliver a significant amount of time-sensitive information while platforms and operators rapidly change locations” (Bordetsky, Benson, & Hughes 2016).

Our systems analysis focused on modeling the impact of different communications network configurations on reliability and the effectiveness of a JF DMO.

The models and simulations were created to determine how well each network configuration could support similar data types. Our hypothesis is that mesh networks would provide clear benefits versus star networks in a littoral environment.

Findings and Conclusions

The backdrop of this study was a series of three JF DMO scenarios designed to degrade the radar capabilities on a Country Red reef island outpost. The scenarios used a combination of air and sea assets with varying capabilities. Scenario #1 was a direct assault on the target radar by a SEAL squad in cooperation with a Combat Craft Medium, a Navy Littoral Combat Ship, an Air Force MQ-9, and a Scan Eagle. Scenario #2 removed the MQ-9 but inserted an Army Logistics Support Vehicle outfitted with Containerized Missile Systems. Scenario #3 combined all assets of Scenarios #1 and #2.

The purpose of the scenario models developed for this study was to help give the reader a better understanding of how the tightly coupled data type, data rate, and desired network capabilities impact the network design, while highlighting the design constraints of the implemented network. The simulation results were used to define a baseline reference and traceable data requirements to support a tactical network designed for a JF DMO.

Network setups are often depicted by their topology, which is the physical way in which the nodes within that network are arraigned and can communicate (U.S. Army Engineering Division, 1984). This research compared a traditional Star network, against a multilayered Mesh communications network and quantified how the arraignment of those links might affect operations. The most widely used topology for a wireless network is that of a star geometric pattern. A star topology consists of a central node through which all information flows. In the star format, all information must be sent and received from each participating asset and routed through the central hub. The central node in this configuration represents a single point of failure; if the central node is taken offline, the entire network will go down.

A multilayered tactical wireless mesh network refers to the process through which information is shared within a network. A mesh network describes a configuration where each node has the capability to communicate and can both send and receive messages to one another. In a mesh, the nodes are self-organizing and automatically establish on an as-needed basis (Shillington & Tong, 2011). There were two communication architectures modeled that were based on line of sight (LOS). To be LOS, there must be little to no obstructions between the transmitter and the receiver. Geographic features like mountains and the curvature of the Earth along with natural features like trees that block the transmission path create a connection type that is called beyond line of sight (BLOS).

BLOS architectures were used for over the horizon communications and have the advantage of poor detectability by near-peer LOS detection systems. Two types of BLOS communications architectures were implemented using bent-pipe or hub-relay structures. Both architectures were represented in the model to account for the time delay inherent in each for a message to reach its intended target node or hub. For evaluation, both LOS and BLOS threshold models were created in Microsoft Excel. The simulation results were then used to determine the desired message completion rates and network parameters for ExtendSim simulations. Excel modeling was also used to validate and modify position reporting rates, based on the type of platforms used in the mission scenarios. ExtendSim was used to model discrete

network performance and evaluate user demands introduced by changing network and parameters. Finally, MATLAB was used for post processing and analysis of the data-logs generated by the ExtendSim simulations.

Network configurations had the most impact on the overall performance based on the application data requirements for interfacing with dependent joint assets. Delay and network reliability for both unicast and broadcast traffic were performances measured in the network configurations. Critical design factors that impacted the system performance were related to the data transition requirement, message transmission unit sizing, messaging overhead for network control, encryption, and emission controls. Network design considerations need to support the data requirements for applications and services to be effective. To enhance JF DMO, strong consideration should be given to the messaging between assets to optimize the amount of data that needs to be transmitted. The message size directly impacts the network configuration performance. Network responses are based on how it handles messaging transmission, data rates, location of network controllers, and how external data is injected and distributed over the network.

Recommendations for Further Research

We recommend that future researchers address the following: determine optimal battlefield reporting for higher confidence in human decision making based on situational awareness, research scalable satellite communications networks to support larger user bases into the thousands, research in the predictive algorithms to predict position reporting with minimal data reporting from users, and research into the benefits of moving network routing capabilities from radio frequency communication systems into warfighting computing devices, using software-defines networking technologies.

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NPS-19-N191-C: Joint Fires in Support Distributed Maritime Operations

Researchers: CAPT Scot Miller USN Ret. and Dr. Dan Boger

Student Participation: No students participated in this research project.

Project Summary

Traditionally Joint Fires (JF) implied naval and air forces supporting land forces. JF in support of distributed maritime operations (DMO) turns that notion on its side, and suggests using JF to support naval forces. DMO, while not precisely defined, generally describes naval forces where firepower is distributed, making counter targeting more difficult and increasing the probability of engagement success. This research explored considerations for such a change, first, by reviewing current tactical approaches

and pondering possible changes across the doctrine, organization, training, material, leadership, personnel, and facilities (DOTMLPF) spectrum, and second, by interviewing practitioners of many of the components of what JF for DMO requires, such as networking, sensing, weapons employment, and logistical movements.

In our work, three themes emerged, including: first, many weapons, platforms, sensors, and network combinations already exist that would support JF for DMO, but no cohesive approach lives, second, numerous DOTMLPF issues require attention, and finally, JF for DMO requires diverse logistics support, probably arranged across services. While JF ISO DMO remains a viable concept, considerable work remains.

Keywords: *Joint fires, JF, distributed maritime operations, DMO, doctrine, organization, training, material, leadership, personnel, and facilities, DOTMLPF, tactics, techniques, and procedures, TTP*

Background

National strategic objectives drive naval operations; the objective may be to deny another navy water space or achieve maritime dominance. Strategic objectives are crucial in deciding the ways and means to accomplish the goals, but this research was not designed to prove any particular hypothesis. Rather, because JF for DMO is a nascent concept, the objective was to survey the existing literature/information and to develop supporting ideas.

JF is simply the employment of weapons on enemy targets, but more formally, “joint fires that assist air, land, maritime, and special operations forces to move, maneuver, and control territory, populations, airspace, and *key waters*.” [emphasis added] (Office of the Chairman of the Joint Chiefs of Staff, 2019).

DMO is a new naval operational concept where many smaller warships spread out and leverage distributed sensors, which increases targeting confusion to the enemy and enables the Navy to shoot effectively first from many different directions. In the maritime realm, the Navy remains the dominant force, but peer competitors are building large fleets capable of engagements with our Navy. In maritime battle, the winner usually achieves a time-honored principle: “**Shoot effectively first**” (Hughes, 2009). JF for DMO are designed to augment that tactical goal in support of broader strategic objectives. Many platforms deliver fire. Examples include Tomahawk missiles, Marine Corp rockets, Army missiles, and Air Force AC-130s gunships.

While “shoot effectively first” is a simple statement, each word implies significant meanings applicable to JF for DMO. **Shoot** signifies having the capability and permission to actually fire. It also means that you must have the ability to shoot. Today, the U.S. Navy finds itself outraged by weapons deployed by several peer competitors. The second word is **effectively**. One must ascertain where is the target, what is its identification, and what is its intent? These are not trivial tasks, and this precept implies the importance of remaining hidden from the enemy. In the past, Navies used weather and islands to mask themselves from an enemy, but now, satellites, drones, and other imaginative sensors make hiding from the enemy ever more difficult. **First** is the last word of this axiom. It implies better scouting than the adversary, weapons that effectively engage the targets, and the availability of signals to communicate firing messages.

Findings and Conclusions

The literature review and discussion with subject matter experts both in person and through online naval forums concludes that JF would add value across all components of the axiom, “shoot effectively first.” JF capabilities have an existing set of scouting and signaling capabilities.

Employing JF to the Navy’s complement of weapons, sensors, and signaling would add numbers and variety to these fires’ components, complicating the enemy’s defensive thinking, scouting, and fleet positioning calculus.

Significant issues exist for employing joint fires in this new way, though. There are significant DOTMLPF issues that need resolution. While doctrine supports JF for DMO, tactics, techniques and procedures (TTP) needs refinement. The Marines experimented with land-based rockets aboard ship, but who owns them aboard ship and directs their use? Also, JF for DMO requires challenging cross domain (air, sea, and land) logistics support, and much work exists to sort out these challenges.

Recommendations for Further Research

This research is the first of a two-year effort; JF are one option available to the Joint Force Commander. We recommend further exploration of force structure options, such as reinventing PT boats, arming merchants (Harris, 2019) with missiles, and flotillas of manned and unmanned surface vessels working as hunter killer teams (Kline & Hughes, 2013). Other ideas include thousands of unmanned surface sensors, such as Waveglider, a Venetian blind contraption that uses waves to power itself, and Saildrone, already in use in many oceanographic research capacities.

We also suggest further research into the logistical challenges of establishing JF for DMO. Sustaining forces in contested areas is hard, and the following ideas deserve more consideration: pre-positioning, contingency contracts, steady approach to exercise-related infrastructure development, and unmanned logistics support systems (Harvey, 2013). However, by embracing small sizes and distributed operations, one emerging idea is that logistics forces can be survivable because they remain aware regarding when and how long to operate within ranges of various weapons classes. Also, since the assets are small, they may be unattractive to adversaries that have limited inventories at operational ranges.

Finally, there are organizational and personnel issues needing further study. One idea is to rig vessels for unmanned operations and remove crew when hazards increase. Another observation is that the current fleet architecture induces caution in commanders. Can the Navy redesign its fleets so that they unleash the aggressiveness and creativity of our commanders? Another suggestion asks whether the Navy can produce enough missiles that they become ammo instead of silver bullets. Such a result would enable designing flotillas for maximum firepower, both instantaneous and sustained.

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NPS-19-N239-A: Testing Multiple Credit/Blame Assignment Methods for Learning

Researcher: Dr. Neil Rowe

Student Participation: Mr. Eric Skalnes CIV INT

Project Summary

Technological surprise is an important concern of U.S. military organizations in a world in which the U.S. no longer has an advantage in many technologies. Technological surprise can be a new weapon, tactic, or strategy. Science and engineering can advance differently in other countries and result in surprises that provide an asymmetric advantage to an adversary. This work used the example of novelty in military vehicles, and we studied evolutionary algorithms to construct novel vehicles. Evolutionary algorithms model biological evolution and mimic the random mutations and crosses in populations, using a measure of “fitness” to determine the survivability of a particular offspring. For vehicles, fitness can be calculated from four factors: effectiveness, novelty, frequency, and cost, where the first two increase fitness and the second two decrease it. Effectiveness was based on measures such as weight, maneuverability, potential speed, material out of which it is constructed, and the degree to which it can occur in swarms. Novelty was based on dissimilarity to the most-similar known vehicle. Frequency was based on the number of similar vehicles likely to be encountered today. Cost was based on the material, size, and power. Data sources used in this study were a broad range of material on technological surprise. We also conducted some experiments with a simple program. Our experiments showed a number of surprising results that would provide decision-makers with challenges. We were also tasked with exploring the notion of surprise in the Libratus poker-playing program, and we concluded it had some, but not much military applicability.

Keywords: *technological surprise, evolutionary algorithms, vehicles, military, unknown unknowns, fitness, mutation, crossing, Libratus*

Background

Evolutionary algorithms are a form of machine learning, which is an important subarea of artificial intelligence in computer science. They can be used to do planning. They are a form of unsupervised learning, which means they do not use training examples but instead use feedback in the form of a fitness function, which ranks alternative solutions. In these operations, candidates are repeatedly “mutated” and “crossed” to produce new items, where mutations produce small variations on items and crosses combine properties of two items to get a new item. Evolutionary algorithms are intended to find novel and surprising solutions to problems, so they would seem a good way to anticipate technological surprise.

Findings and Conclusions

This work was designed to aid strategic planners. It studied the feasibility of a software tool to better anticipate technological military surprises, and in particular, to anticipate “unknown unknowns” that represent novelty which could cause asymmetric advantages for an adversary. N2/N6 is concerned with using information technology to address Navy needs, and this could provide them with a software tool for an important part of the Navy mission.

Some of our demonstration experiments showed that evolutionary algorithms were feasible and effective in find plausible surprising military vehicles. Our results also indicated that these algorithms were not difficult to implement and customize for particular military threats. It showed their results could be easy to understand. Therefore, our hypotheses about how they could be effective were confirmed. However, as we have only studied the examples of military vehicles malicious software, and we cannot guarantee equally good results with other military technological surprises.

We were also tasked by the sponsor to investigate the Libratus artificial intelligence-based poker-playing program what lessons it provided for military strategy, since it has generated surprises to help beat professional poker players. We discovered that much of the software’s impact was due to learning overnight from game play the previous day and this rarely has a counterpart in military strategy. Some of its impact was due to a decision-theory technique called “regret minimization” which better models human decision-making, and this is worth investigating further though its effects were not dramatic.

Data sources used in this study were a broad range of readings of relevant material analyzing the problem of technological surprises and how they can be better anticipated. We also constructed a simple program to generate surprises and experimented varying its parameters to see how they affected success. Student Eric Skalnes developed the first version of the program. There was an optimum number of parameters to vary, an excess of which slowed progress in finding surprises. An important parameter in our experiments was the size of the starting population of random items, since having it too small greatly impeded subsequent discoveries in these experiments.

Recommendations for Further Research

The approach using evolutionary algorithms appears promising, and could be applied to other military challenges such as anticipating new sensors, new weapons, new tactics during combat including new cyberattacks.

NPS-19-N324-A: Increasing Sensor Efficiency for Small Satellite Maritime Domain Awareness

Researchers: Dr. Mark Karpenko, Dr. I. Michael Ross, and Dr. Ronald Proulx

Student Participation: No students participated in this research project.

Project Summary

Small satellites in low-earth orbit can be used to enhance maritime domain awareness activities. A planning algorithm that can generate imagery collection sequences rapidly, in real-time or near real-time, is needed for effective use of these systems. In this project, we explore a new concept for real-time mission

planning that can generate high-value collection sequences while (i) automatically accommodating operational constraints such as satellite slew rate limits and sensor keep out zones, (ii) leveraging the physical capabilities of a small satellite attitude control system for faster slews, and (iii) satisfying engineering feasibility for flight. Insertion of a high-priority collection is also supported with the least disruption to the mission.

The elements of the new concept are illustrated over a deterministic target set for a simplified proxy problem. The results suggest that further developing the new planning algorithm can enable enhanced collection capacity for a constellation of small satellites, and that future work should explore extensions of the concept to uncertain target sets.

Keywords: *maritime domain awareness; small satellites; real-time mission planning; optimal search*

Background

Part of maritime domain awareness is concerned with understanding the movement of ships that can impact the safety and security of the United States. Collecting information on dark targets is of particular importance because these ships cannot be identified using automatic identification system signatures. Small satellites in low-earth orbit offer one potential solution for monitoring dark targets through the use of electro-optical or similar sensors. Operating a small satellite system for maritime domain awareness requires a planning algorithm that determines sequences of targets for monitoring from a potentially over-subscribed set. A good plan will maximize information gain over a given pass.

A conventional planning process is multi-step and relies on concepts from the field of graph theory. A planning graph comprises two parts: edges and vertices. A set of N vertices represents attributes associated with collecting on a particular target of interest, such as the presumed geographic location of a dark target and the target's information value. Edges encode attributes associated with the activities that must be performed in order to execute a collection, such as a maneuver. To maximize the utility of the small satellite, the sequence of targets yielding the largest overall collection value is sought—this is the so-called orienteering problem.

Findings and Conclusions

This study explores an alternative planning methodology with the goal of increasing the efficacy of satellite collection planning towards real time. Solving an orienteering problem for satellite collection planning in real time is not possible because it is necessary to first determine the N^2 edge weights by solving a set of dynamic optimization sub-problems and then iterate through various candidate target sequences to find the sequence that maximizes the utility of the collection plan. To obtain a collection plan in a given time frame, heuristics are often used in an effort to simplify the graph. This is typically done by removing vertices or using overly simplistic vehicle models to reduce computational load. Then, because the graph problem is only an abstraction, the operational constraints need to be checked in a post-processing step to ensure all practical requirements are met. In this graph-centric framework, real-time situational information cannot be readily ingested. The result is a bottleneck in the tasking, collection, processing, exploitation and dissemination process.

In contrast to the status quo approach, where dynamic optimization sub-problems are ancillary to solving the graph, we flip the problem statement. That is, we instead formulate and solve a dynamic optimization problem with a graph imbedded as an ancillary sub-problem. The new concept necessitates the use of a new mathematical framework for describing the attributes associated with the vertices of a graph in terms

of a real-valued variables that are conducive to dynamic optimization theory. In this study, we implement a particular mathematical problem formulation to illustrate the possibility of solving a satellite collection planning problem using real-value imbedding and without solving a graph.

Using these new concepts, the time needed for maneuver planning is dramatically reduced so the planner can incorporate situational information as it becomes available. The fast planning algorithm can accommodate improved models of spacecraft physics, and has the potential to revolutionize the way small satellites are operated to support maritime domain awareness and similar activities.

Recommendations for Further Research

Because the precise location of dark targets may not be known in advance, the locations of targets for collection were considered to be deterministic. To advance the concept beyond this study, a belief state model can be used to assign probability distributions to the locations of uncertain targets. Further research should explore how a belief state model can be incorporated into a dynamic optimization-based planning algorithm. Additional work should also be done to map the concepts to a practical small satellite system of interest to the sponsor.

NPS-19-N355-A: Understanding the Sources of Illicit Drug Bale Wash-Up (Interim Report)

Researchers: CDR John Joseph USN (ret.), Dr. Tetyana Margolina, Dr. Leonid Ivanov, and Dr. Timour Radko

Student Participation: No students participated in this research project.

Project Summary

Counter-drug agencies have encountered many illicit bales of drugs wash up on shore of beaches around the Gulf of Mexico region, yet it is not clear where the packages originated or how long the packages had been drifting. This trend has almost quadrupled in the number of cases in the past few years. This study will apply high-resolution oceanographic modeling at NPS to provide a physics-based solution that narrows the likely origins of the drifting drug bales that have washed ashore and will shed light on their “patterns of life.” The study will integrate critical intelligence information collected by the US Coast Guard, DEA, Navy and other drug enforcement agencies to help guide and constrain the model to produce statistically significant, realistic output. Results from the study will also provide insight on the methods used by drug smugglers to move their illegal cargo. At least two modeling approaches will be employed to statistically trace the past movement of the drug bales. One method uses a forward-motion approach that starts with a gridded distribution of simulated bales that are driven by the currents and wind stress derived from a high-resolution ocean model to assess where and when the bales would reach locations of known wash-ups. A second method uses an adjoint modeling approach that employs a time-reversal method; that is, simulated bales are backed-up along reversed tracks from their landing locations driven by time-reversed model physics. Information based on the insight of experienced “on-scene” enforcement personnel (made available via USCG and JIATF South) will provide constraints on how the model results will be interpreted. For example, washed-up bales known to be 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 will be conducted to provide statistically valid results for the study.

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 into 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 USCG or 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 4-5 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

In the initial phase of the study, we applied a forward-motion modeling approach to help understand the physical mechanisms that determine the movement of drug bales that may originate from the Yucatan region in the Gulf of Mexico and Florida Bahamas flows, and to estimate their drift behavior quantitatively. Travel times were estimated for packages drifting along trajectories seeded in the Yucatan Channel, propagating into the Gulf of Mexico and then through the Florida Straits into the Florida and Bahamas coastal areas. Mean subsurface velocities applied to estimate the travel times were derived from the high resolution (3 km) RNCOM ocean model using a 10th order wavelet decomposition (Ivanov and Chu, 2019). Possible mechanisms for trapping drifting packages within the Florida and Bahamas coastal areas are discussed. Preliminary calculations demonstrate that most passive drifters are transported to a Florida-Bahamas coast by tides. However, surface waves and winds also can play an important role in this process.

The general conclusions obtained by the project thus far are as follows:

1. The modeled circulation with the spatial resolution of 3 km allows us to estimate some mechanisms of motions of drug containers including influence of tides on these containers. Estimations of the travel times for passive drifters along several prevailing trajectories exceeded those estimated earlier (see, for example, Lugo-Fernandez, 2006).
2. The current work suggests that a basic mechanism for the Florida coast responsible for the beaching of drug containers is the classical tides. This mechanism is evident outside the Gulf Stream in the area with coordinates: 27–30°N between 79–81°W.
3. Real drug bales had different geometry than the one assumed in the initial modeling efforts (spheroidal “particles” of the size which was smaller than the spatial scale of the circulation).

Preliminary numerical experiments show that accounting for the container shape will result in higher degree of level of freedom and the container motions may change.

4. The meandering Florida current re-distributes the moving particles in the near coast areas where they can be subsequently moved onto the coast by wind (which is not resolved in the initial modelling efforts) or wind waves (which have not been accounted for in the model). These factors will be studied in more details.
5. Our numerical estimations demonstrated that the degree of turbulent intensity (especially in the Florida coastal area) plays an important role in pushing out free particles from the main jet and then in their transportation onto the coast. A strong particle drift can be found in the area with coordinates: 24–26°N between 78–82°W.

The current work is in the early stages of getting the model “up and running” and has provided useful preliminary results. One of the primary concerns is being able to represent the drug bales in the model in a realistic way so that the important physics that drive the drift is captured. For example, the density of bales can determine how the bales ride in the water which, in turn, influences how much the winds and currents, which may not be in the same direction, control the net drift of the packages. Limits at which the model is no longer valid must also be considered. For instance, once the bales get very close to shore, there are likely to be small-scale physics that the model cannot resolve that may influence the transition of the bales from the sea to shore. Intelligence information received via the USCG District 8 and the dialogue with some of the on-scene counter-drug personnel has helped “tune” the model to provide realistic results. Location of landfall or at-sea intercept sites, images of recovered packages, descriptions of packaging and similar intelligence provide insight on how best to initialize the information in the model. Continued collaboration will enable the model to produce realistic scenarios and reduce uncertainty of the trajectory predictions.

Recommendations for Further Research

Our present investigation lays the foundation for further work on methods to improve estimations of how the drug bale are moved through the ocean by environmental factors and tend to wash up at some common locations. Continued efforts to incorporate intelligence information provided by drug enforcement agencies with physical oceanographic conditions derived from oceanographic modeling is needed. Validation of the performance of the model based on tracking of real and simulated drifting drug bales would allow adjustments that are likely to increase confidence in the results, thus providing law-enforcement personnel a reliable, efficient tool to meet their objectives.

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N3/N5 - PLANS & STRATEGY

NPS-19-N001-A: Maritime Strategy and Naval Innovation (Continuation)

Researchers: Dr. James Russell and Dr. James Wirtz

Student Participation: LT Robert Putrino USN

Project Summary

The Navy is addressing fundamental changes to its strategic focus, enabling it to confront strategic challenges in the Indo-Pacific region. The emergence of near peer geostrategic competition has become the central planning focus for the Navy as it considers its plans, programs, budgets and policies over the rest of this century. This requires the re-orientation of maritime strategy, and the employment of naval power away from the emphasis on supporting land operations over the last quarter century in the irregular wars in Iraq and Afghanistan. This study addresses the strategic implications of near peer competition in the Indo-Pacific region, which involves a variety of new actors that will play a role in the US-China rivalry in this geographic domain.

Keywords: *strategy, planning, programming, Planning, Programming and Budgeting System, PPBS, ind-pacific, China, India, coercion, deterrence, war*

Background

This project marks the fourth year that SIGS/NSA has supported the N50'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.

Findings and Conclusions

A naval buildup is underway throughout the Indo-Pacific region, and spending could grow by 60 percent over the next five years. The Naval buildup reflects complex regional strategic 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, and the prospects for escalation are far more dangerous than previously realized. Crisis-management and political decision-making will be more difficult throughout the Indo Pacific as navies avail themselves of the latest technologies.

Recommendations for Further Research

The Navy needs to rediscover long-forgotten writings on deterrence, coercion, and strategy to analyze the dimensions of the strategic environment in the Indo-Pacific. The results of the study expand the knowledge necessary to address this strategic problem. The findings confirm the analysis in the security studies literature about the necessity to become grounded in deterrence theory, coercive strategies, and war-planning contingencies.

NPS-19-N258-A: Assessing the Implications of Changes in Russia's Strategic Posture

Researchers: Dr. Mikhail Tsypkin and Dr. David Yost

Student Participation: No students participated in this research project.

Project Summary

To what extent is Russia primarily interested in maintaining stable mutual deterrence? To what extent does it look beyond that goal to preparing for the operational use of nuclear weapons for political and strategic advantage? In our research, we examined the implications of changes in Russia's strategic posture, most notably since President Putin's announcement on 1 March 2018, of projected "super weapons," also called "novel systems." These include a hypersonic aero-ballistic missile, a nuclear-powered cruise missile, the Sarmat heavy intercontinental ballistic missile, and the nuclear-armed nuclear-propelled "Status 6" unmanned submarine (also known as Kanyon and Poseidon). Putin and other Russian officials have asserted that Moscow is pursuing these capabilities and others, including conventional forces and cyber and space assets, in response to U.S. missile defenses and the policies articulated in the 2018 U.S. Nuclear Posture Review. In addition to the several novel systems announced by Putin in March 2018, in February 2019, Putin threatened to develop and deploy Zircon hypersonic missiles on ships within range of the continental United States, which would be capable of delivering a decapitating strike against the US National Command Authorities, putting the United States at risk.

After a review and analysis of current literature and discussions with experts, we determined that the principle operational stance among Russian leaders today regarding nuclear development and strategic posturing is one of manipulation and intimidation. These tactics are used in order to influence public opinion at home and abroad, and to register the Kremlin's displeasure with certain actions of the United States and North Atlantic Treaty Organization (NATO).

Keywords: *Russia, nuclear weapons, North Atlantic Treaty Organization, NATO, deterrence, hypersonic missiles*

Background

This research was inspired by the work performed for the sponsor in previous fiscal years. The previous research efforts include Responding to Russian Noncompliance with Nuclear Arms Control Agreements (Fiscal Year 2016) and Evolving Russian Views on Nuclear Weapons and Their Significance for the United States and the North Atlantic Treaty Organization (NATO), (Fiscal Year 2017).

Some allied observers have speculated that Russia could seize a piece of alliance territory and warn NATO allies that Moscow would be prepared to use nuclear weapons in order to retain it. Allied observers have not reached a consensus as to the extent to which Russian capabilities have established limits to French, British, or U.S. nuclear protection. Some observers suggest that the Russians may plan for a limited war, with or without nuclear weapons, based in part on their snap capacity for large-scale force mobilization and movement. Similar speculation holds that Russian aggression could take the form of a conventional-warhead SSC-8 strike against one of the Baltic States. In addition, the Russians might intend to divide NATO by threatening nuclear (or non-nuclear) retaliation against any NATO reply to a Russian attack.

Allied observers have also emphasized the domestic electoral purposes behind Putin's articulation of the March 2018 list of super weapons, setting aside the nuclear-propelled cruise missile concept as the least plausible of the super weapons discussed by Russian authorities in recent years.

Findings and Conclusions

While allied observers generally agree that the essential objective of Russia's super weapons is to be able to penetrate or evade U.S. missile defenses, there is much speculation as to other motivations and objections. The theories of allied observers cover a wide range, including that the Russians have publicized Putin's super weapons because Russia has nothing else to boast about except energy resources, and that the purpose of Poseidon may be to deepen doubts among U.S. allies about the credibility of U.S. extended deterrence commitments, or conversely, doubt as to whether the Poseidon nuclear-powered undersea attack drone would add much value to Russia's strategic capabilities or even require a response.

Our research indicates that the Russians may, however, see Western public intimidation advantages in the Poseidon. This seems to be one of the overall purposes of Russian super weapons as they present Russia as being at the forefront of technology development, thereby granting it international status and influence. However, the spectrum of views in NATO expert circles on Russia's super-weapons includes skeptics who question the general feasibility and affordability of these weapons. In fact, paradoxically, one effect of Russia publicizing its super-weapons is that the Russians may intensify a competition with China and the United States that they simply cannot afford.

In support of this theory, there is a notable lack of detail in Putin's February 2019 threat to deploy Zircon hypersonic missiles against U.S. National Command Authorities. This raises questions about the hypersonic missile's affordability and technical-industrial maturity. According to Putin, the Zircon missiles would be based on maritime platforms, submarines or surface ships, which would require a level of robust and reliable communications that Russia does not yet possess.

These actions are compounded by the fact that the formally agreed to Soviet-U.S. definition of strategic stability in the June 1990 START negotiations has lost prominence. The agreement envisaged measures to remove incentives for either side to launch a nuclear first strike and to establish an appropriate relationship between strategic offenses and defenses. In recent years, high ranking Russian officials, including President Putin, have regularly used the term "strategic stability" to express critical views of U.S. policy. For example, Russians have asserted that the United States or NATO have threatened strategic stability by actions such as the U.S. withdrawal from the Anti-Ballistic Missile Treaty, and the Intermediate-Range Nuclear Forces Treaty, the enlargement of NATO, or the conduct of NATO exercises in Norway or in the Baltic states, etc. In addition to accusing the United States or NATO of threatening strategic stability, the Russians have used the term to express threats, to support propaganda purposes such as claiming that the Americans are unwilling to engage with them on arms control, and to construct arguments not only against U.S. missile defenses, but also against projected U.S. space defenses and non-nuclear strategic strike systems.

Recommendations for Further Research

Future researchers should examine the full range of implications arising from changes in Russia's strategic posture. Because Russian miscalculations could present risks of conflict, it remains essential for the United States and its NATO Allies to develop a more discerning and comprehensive understanding of how the Russians view their nuclear weapons and other instruments of influence, intimidation, coercion, and combat. As in the past, Russian concepts such as "de-escalation" and "strategic non-nuclear deterrence" deserve monitoring and careful analysis, together with Russian grand strategy and operational concepts, for the employment of the novel systems announced as under development in 2018-2019.

NPS-19-N260-A: Implications of Russian Strategic Changes on China

Researcher: Dr. Michael Glosny

Student Participation: No students participated in this research project.

Project Summary

This project addressed the following research question: how has China perceived and responded to Russia's recent strategic modernization? This project employed a qualitative social science methodology and examined Chinese-language books and articles published by military officers, government officials, scientists, government think-tank analysts, and university scholars, supplemented by a research trip to Beijing and Shanghai for discussions with experts. The findings show that China characterizes Russian nuclear strategy as defensive, and that Russia's increased emphasis on nuclear weapons is designed to deter the West. Overall, the findings showed that China does not see Russian nuclear modernization as a concern or threat, because the two countries have a positive bilateral relationship. Further, China can understand the rationale of a weak Russia in putting more emphasis on nuclear weapons, given threats from NATO and the United States. In short, this research found little evidence that China is adjusting its nuclear doctrine, nuclear strategy, or nuclear modernization efforts in response to Russia.

Keywords: *China, Russia, nuclear, strategic, Intermediate-Range Nuclear Forces Treaty, INF Treaty, Sino-Russian relations, great power competition, missile defense, nuclear strategy, nuclear doctrine, strategic weapons, strategic modernization*

Background

In an era of "great power competition" in which the United States is dealing with the challenges of revisionist Russia and China, the triangular relationship has become more important. There is vast and developing literature on each of these three powers, their respective bilateral relations, and the strategic nuclear modernization efforts of each country. Many scholars have examined the U.S.-Russia nuclear relationship and the U.S.-China nuclear relationship, but there has been very little analysis of the Sino-Russia nuclear relationship. Moreover, analysis of China's nuclear modernization has emphasized threats from U.S. modernization and domestic political actors as the most important drivers, without consideration of the effects of Russia's nuclear modernization on China. This project analyzed Chinese perceptions and responses to Russia's recent strategic modernization. As one of the first projects to examine this important and understudied issue, our main hypothesis was that China does not perceive Russian modernization as much of a threat, and therefore, in response, China has not made adjustments to its nuclear capabilities, doctrine, or deployments.

The purpose of the study is to fill a knowledge gap, which is significant to OPNAV N-5, the broader US Navy, and the broader academic study of international security affairs. The main objective was to collect data from Chinese-language sources to better understand and analyze how strategic changes in Russia have affected Chinese nuclear thinking, nuclear doctrine, and nuclear capabilities. Studying China's perceptions and response to Russian modernization can help us understand the current and likely future direction of China's own modernization, and potential changes in development and deployment of Chinese assets, especially naval platforms. Moreover, examining Chinese views on Russia's provocative behavior provides insight into the possibility of driving a wedge between Russia and China, and working together with China to pressure Russia on nuclear and arms control issues.

Findings and Conclusions

To best analyze and explain Chinese assessments and strategic responses to Russian modernization, this project employed a qualitative social science methodology and utilized existing social scientific theories of threat perception and strategic force postures. The work began by analyzing the limited English-language literature on this topic, but the main source material and value-added of this project came from a thorough and systematic analysis of Chinese-language sources, in order to provide new information and perspectives that are currently unknown to the US Navy, the US government, and the broader academic world. In this research effort, I collected, examined, and analyzed Chinese-language books and articles published by military officers, government officials, scientists, government think-tank analysts, and university scholars on two main literatures: 1) Chinese assessments and analysis of its strategic nuclear environment; and 2) Chinese analysis of Russia's security policy and broader Sino-Russian relations. To supplement these written sources, and discuss Chinese strategic thinking and assessments of changes in Russia, I also conducted a research trip to Beijing and Shanghai to meet with military officers, scientists, government think-tank analysts, and university scholars.

This research showed that Chinese experts clearly recognize that Russia's nuclear strategy and doctrine have evolved since the end of the Cold War, including an increasing emphasis on the role of nuclear weapons, but they do not view this evolution as particularly provocative or dangerous. U.S. government officials and experts, most clearly in the 2018 Nuclear Posture Review, have expressed strong concerns about the destabilizing impact of Russia's recent moves to develop new nuclear capabilities, emphasize tactical nuclear weapons and limited use of such weapons, conduct more aggressive nuclear exercises, and adopt a risky and offensive doctrine of "escalate to de-escalate" and an approach of using nuclear weapons to support limited offensive conventional operations. Chinese experts argue that "escalate to de-escalate" is an American term, they are not sure it is a proper characterization of Russian nuclear doctrine, and there has been no official government policy document endorsing or reflecting such a strategy. They note that what the Americans describe is risky and escalatory, and Chinese experts argue that Russia is too prudent to adopt such an approach. Further, in terms of capabilities, they argue that most of Russia's modernization efforts are on replacement rather than new modernization, and Russia is too poor to field new weapons in large numbers.

Although Chinese experts notice some troubling recent speeches and behavior from Russia on the nuclear front, they emphasize that Russia's increased emphasis on nuclear weapons is defensive and purely to enhance deterrence against the United States, which itself is trying to undermine the nuclear balance and strategic stability. Chinese experts also adopt a different position than the United States on the Russian violation of the Intermediate-Range Nuclear Forces (INF) Treaty, which forced the U.S. to withdraw from

it. As China is not a party to the INF Treaty, officials and experts maintain that it was not their place to offer a position as to whether or not Russia's missile violated the range restrictions in the treaty. Most Chinese experts argue that this was a small technical violation, which often occur in arms control, and did not need to lead to the U.S. withdrawal. Moreover, they argue that Russia was transparent and attempted to be very accommodating by inviting U.S. officials to come to Russia to inspect the missile range themselves, but US experts refused and unilaterally abandoned the treaty.

Chinese experts also understand the rationale for why a weak Russia, facing increasing threats would need to increase its emphasis on nuclear weapons. This finding also confirmed our initial hypothesis, and revealed a much deeper and more nuanced analysis by Chinese experts. In the post-Cold War era, Russia's economic power declined and its conventional capabilities are much weaker than NATO. Chinese experts argue that Russia has no choice but to increase the reliance on nuclear weapons and modernize because it faces threats from NATO expansion and the U.S. missile defense programs and nuclear modernization. Moreover, Chinese experts emphasize that new changes in U.S. capabilities, such as developing low-yield tactical nuclear weapons and new platforms, have destroyed Russia's strategic stability.

Overall, China does not see Russian nuclear modernization as a concern or threat because the countries have a positive bilateral relationship and do not see Russia's nuclear forces as targeting China. This confirmed my original hypothesis, but provided much greater supporting evidence than was previously known. Chinese experts argue that the definition of the overall political relationship is most important and influences Chinese views on all aspects of the relationship. In a series of political documents, the two countries have reaffirmed their close relationship and comprehensive strategic partnership. Both sides have mutual trust, respect each other's sovereignty and core interests, and share similar perspective and concerns about the West. Additionally, unlike the U.S. and China, Russia and China have a consistent official dialogue on nuclear and strategic stability issues, which rarely criticizes or questions the other party—they usually spend more time discussing how U.S. behavior has undermined strategic stability and how it can be restored. The countries also have a “no first use” nuclear relations commitment and a stable mutual deterrence relationship. Therefore, China's perception of Russia's non-threatening intentions has resulted in China's relaxed and confident position on Russia's nuclear modernization. Chinese experts also do not accept or endorse arguments that the indirect and second-order effects of Russian modernization represent a threat and/or negative development for China.

While the dominant Chinese view is that Russian modernization is not a direct threat, experts note some concern regarding in terms of arms control and potential crises. In analyzing the overall nuclear environment, Chinese experts observe that increasing the emphasis on nuclear weapons, lowering the nuclear threshold, and developing more usable tactical nuclear weapons are negative developments and challenges for arms control and strategic stability. They observe an “action-reaction cycle” in modernization between the U.S. and Russia that leads to more obstacles for arms control and more challenges for strategic stability; yet experts place more blame on the United States than on Russia for these dynamics. Chinese experts also express a general concern that crises in regional hot spots could become even more dangerous in a context if the nuclear threshold is lowered, and countries are developing and deploying tactical nuclear weapons.

In summary, Russian nuclear modernization has not greatly impacted China's nuclear doctrine or nuclear capabilities. Chinese experts argue that the country's nuclear approach and nuclear doctrine have maintained continuity, and China has continued its “lean and effective” defensive nuclear policy.

When analyzing the international nuclear threat environment, Chinese experts usually do not consider Russia as an important factor or driver. In terms of regional nuclear capabilities, Chinese experts discuss improved missile defense capabilities in Japan and South Korea, other regional nuclear powers such as India, and more recently the need to deter Taiwan independence. It is certainly possible that China feels threatened by Russia, and is using these other countries as excuses for a modernization that also has a Russia element, but there is no evidence to support this and it would be speculation.

Recommendations for Further Research

The findings of this project have uncovered several areas of further research that will be useful for the US Navy and the broader academic community. First, it is important to develop a deeper understanding of how Russia and China perceive a “post-INF world,” what concerns they have about potential U.S. actions, and how they are likely to respond. Second, research analyzing similarities and differences in Chinese and Russian threat assessments from current and future U.S. missile defense capabilities should be explored. Third, it is critical to assess the prospects for maintaining existing arms control treaties, developing new arms control regimes, and how success or failure in arms control will likely shape great power competition with China and Russia.

NPS-19-N290-A: Russian Federation Anti-Access and Area Denial (A2AD) Posture

Researcher: Dr. Donald Abenheim

Student Participation: No students participated in this research project.

Project Summary

This research underscores how Russia's rapidly evolving use of maritime weapons, tactics, and strategy have quickly changed the perception of conflict at sea, and our results reveal that the issues at the heart of this study require more resources and greater command emphasis. The principal investigator and his colleagues examined the evolution of Russian strategy through qualitative policy analysis, augmented by historical analysis and discussions with experts in the United States and Europe. The authors also examined past episodes where strategy and combat may have resembled the challenge at hand. Among primary sources, the most significant were ministerial statements of policy and strategy, the doctrines of the high command, and theoretical military writings, of which there is a long record of in Russian history. Secondary sources included civil and military scholarship, as well as analyses of operations and exercises.

Keywords: *anti access and area denial, Russian Federation, Russian maritime strategy, Atlantic Baltic, Kalinin*

Background

Over the last 15 years, the Russian Federation has revamped its maritime strategy, naval forces, and other weapons in a startling manner, in attempting to restrict the freedom of movement of forces needed to constrain Russian aggression. Moscow has eschewed the approach of the 1970s, in which it sought to build a blue-water fleet on the classic pattern. Instead, the reformed Russian forces have opted to do more with less, emphasizing new shore-based, long-range weapons as well as submarines and surface vessels

operating in a doctrinal scheme of coercive diplomacy, low-intensity conflict, and a singular aggressiveness to exploit strategic opportunities. In the 2008 campaign against Georgia, the lightning annexation of the Crimea in 2014, and geopolitical deployment to Syria in 2015, Russia has displayed how strategy, operations, tactics, forces, and weapons are brought to bear in the realm of anti-access and area denial (A2/AD) in Europe and the Middle East. These offensives have thrown a shadow over the global commons, and threaten to deny the U.S. Navy the untroubled access to the world's littoral waters: the norm since 1991.

Findings and Conclusions

This research underscores how Russia's rapidly evolving use of maritime weapons, tactics, and strategy have quickly changed the perception of conflict at sea, and the results reveal that the issues at the heart of this study require more resources and greater command emphasis. Indeed, the geographical and global expanse of this subject requires a multi-year study, which was not practical in this work. However, five Naval Postgraduate School officer-students will expand upon this research through master's theses expected in 2020.

Recommendations for Further Research

More resources should be devoted to a practical understanding of Russian maritime strategy, and this knowledge should be shared widely with those who have the operational need in the face of Russian aggression. Additional future research should also analyze Russian psychological warfare against the United States and NATO, specifically, the mass persuasion effort to rob the U.S. Navy of its freedom to operate. Other future research may build upon the excellent analysis done at NATO Europe and among other U.S. partners to deter and diminish the Russian A2/AD threat. Further work is also needed for each geographical maritime region (i.e., the Black Sea, the Atlantic, and Russian Pacific littorals), and such research must emphasize the connection between tactical and technological developments, as well as their implications for strategy in this great power struggle.

NPS-19-N305-A: Chinese Security Cooperation with Southeast Asian Countries: Implications for U.S. Naval Operations

Researchers: Dr. Michael Glosny and Dr. Michael Malley

Student Participation: LT Kelly Bischoff USN

Project Summary

This project addressed the following research question: How has China's security cooperation with Southeast Asia evolved and developed in the last five years? In answering this question, we examined the security cooperation activities, such as exercises, arms sales, and high-level defense engagements, the drivers for China's turn to a more proactive approach to security cooperation, and regional countries' responses to Chinese proposals. We employed a mixed method social scientific approach to this question, using quantitative analysis to track the activities and qualitative analysis, including research trips to China, Malaysia, Vietnam, and Singapore, to better understand the Chinese and Southeast Asian perspectives. Our main findings indicate that China has deepened its security cooperation with virtually every country in the region, in almost all types of activities. Although countries like Thailand and

Cambodia enjoy very close security cooperation with China, even countries such as Vietnam, which are more reluctant to do so and have maritime disputes with China, have also deepened cooperation. Therefore, our research determined that the U.S. Navy must adapt and adjust to a regional security environment in which China is conducting exercises and selling arms to Association of Southeast Asian Nations (ASEAN) countries, including U.S. allies, and operating together with these countries in close proximity to U.S. operations.

Keywords: *China, Southeast Asia, Association of Southeast Asian Nations, ASEAN, security cooperation, military diplomacy, arms sales, multilateral security cooperation, Xiangshan Forum, Shangri-La Dialogue, hedging*

Background

For the last decade, U.S. government experts and academics have been focused on China's assertive behavior in Asia, particularly aggressive actions and land reclamation projects in the South China Sea. As a result of this focus, the existing literature has missed another important development: China's proactive security cooperation with Southeast Asia. Little systematic analysis of these activities has been conducted, as most experts dismiss this cooperation as low level, or assume that countries in the region will always chose the United States over China. Although there is not much existing literature on which to draw, the study began with two hypotheses: first, China has become more active in all areas and with all countries in its attempt to deepen security cooperation and second, China be most successful in deepening security cooperation with small countries on mainland Southeast Asia, and will be least successful with U.S. allies and key partners.

Around 2015, China became more proactive in trying to deepen all forms of security cooperation with its neighbors in Southeast Asia. Some Chinese experts argue that this new activism was a natural and gradual development, and part of the 1990s frameworks of broad comprehensive cooperation, which included a vision for deeper security cooperation. Another argument highlights Chinese frustration with the limited effectiveness of economic cooperation leading to improved security relations, and since 2010, the shock of more intense territorial disputes in the South China Sea, and U.S. effective efforts to improve security relations with countries in the region. Moreover, as territorial disputes escalated and countries perceived China as assertive, China recognized the need to use security cooperation and military diplomacy to demonstrate it wasn't a threat, and its neighbors would benefit from China's rise: specifically, with its growing military capability, China now had the capability to conduct exercises and sell more advanced weapons. Lastly, Xi Jinping has been especially supportive of more proactive military engagement in the region, and the People's Liberation Army has supported this position, sending high-level officials to regional security meetings.

Findings and Conclusions

The purpose of this study was to examine a neglected topic and fill a knowledge gap regarding China's security cooperation with Southeast Asia. Understanding this security cooperation and examining the implications is important for understanding how countries perceive China, how much room exists for further cooperation with the United States, and whether or not China is pulling U.S. allies and partners towards China. This study employed a mixed methods social scientific approach, including quantitative and qualitative analysis, and included systematic exploration of English-language and Chinese-language sources, and also included research trips to China, Vietnam, Malaysia, and Singapore.

Since 2015, our research shows that China has dramatically deepened security cooperation with Southeast Asia through bilateral and multilateral channels, including more military exercises, arms sales, port visits, and high-level engagements, which confirms this work's initial hypothesis. For example, China has conducted bilateral exercises with Thailand, Singapore, Malaysia, Indonesia, Brunei, Cambodia, Myanmar, and Laos. Although many of these exercises remain scripted, small, and focused on non-traditional security, this has provided the foundation for future cooperation. However, contrary to our hypothesis, China's exercises are the most frequent and sophisticated with Thailand (a U.S. ally) and Singapore (a close U.S. partner). In addition, China has also held multilateral exercises, such as the first ASEAN-China Maritime Exercise, involving all members of ASEAN. China has also sold arms to Cambodia, Myanmar, and Thailand for many years, but recently it has expanded such arms sales to include the sale of submarines to Thailand and maritime patrol vessels to Malaysia; this also runs counter to our original hypothesis. China has also worked to deepen cooperation through multilateral regional mechanisms, even creating the Xiangshan Forum, which is attended by most senior defense officials in the region.

Although there is a wide range of cooperation with China, with Thailand and Cambodia enjoying high levels and Vietnam much lower levels, all countries in Southeast Asia express similar themes in regarding their openness to such cooperation. Although Singapore is often referred to as the exemplar, all countries want to maintain balance and stable relations with the U.S. and China to benefit from both countries. Cooperating with China signals that these countries are not choosing a side, and also shows the U.S. that they welcome China's positive contributions in the region; when countries participate in an exercise or engagement with the U.S., the need to maintain balance then puts pressure on them to cooperate with China as well. It is also clear that as China has become more powerful and proactive in proposing security cooperation, it has become increasingly difficult for these countries to say no to China. Lastly, experts in several countries point to uncertainty about the Trump administration's commitment to the region as yet another reason to cooperate with China.

Recommendations for Further Research

These findings suggest several potential areas of future research that will be valuable for the U.S. Navy and broader academic community. First, a more comprehensive study is warranted to examine the security cooperation between China and each of the ten ASEAN countries, both through bilateral and multilateral challenges. Second, even though China has only recently become more active in security cooperation, a more comprehensive picture could be drawn by comparing the levels and types of security cooperation Southeast Asia has with the United States and with China. Third, analysis that posits different degrees of Chinese success in deepening security cooperation, and examines the implications for U.S. military operations and U.S. allies and partnerships in the region would also be beneficial.

N4 - FLEET READINESS & LOGISTICS

NPS-19-N068-A: Managing Materiel Distribution in an Uncertain Environment

Researchers: Dr. Michael Atkinson and Dr. Moshe Kress

Student Participation: ENS Richard Hicks USN

Project Summary

The U.S. Navy's supply chain stretches all around the globe, and is needed to support the fleet in many theaters to maintain maritime superiority. However, supply chains can be subject to disruptions that slow the flow of supplies throughout the network, and such disruptions may severely hinder the readiness of ships operating in distant theaters. The most common culprit of peace-time supply chain disruptions is adverse weather, which is especially true in waters that are prone to major tropical storm systems. With these concerns in mind, this project formulates six optimization models aimed at advising logistics mission planners in how to best prepare for and/or respond to these contingencies. The models presented fall into both the reactive family, responding to the disruptions as they occur, and the proactive family, planning for disruptions based on their likelihood before they occur. These models utilize optimization and probability components in different ways to generate supply routes through a network vulnerable to uncertain disruptions. The results are analyzed in order to determine the suitability of use of the models in several disruption scenarios.

Keywords: *logistics, supply chains, disruptions, network models, shortest path*

Background

Logistical support is crucial to the success of most military operations and allows the U.S. Armed Forces to maintain operational flexibility and superiority. Our focus is on U.S. Navy logistics and how to maximize the likelihood of effectively supporting ships, aircraft, and personnel deployed around the world. Degradations to a logistical supply network may interfere with the U.S. Navy's ability to operate effectively in a forward theater. The U.S. Navy supply chain is subject to disruption that may impede the flow of supplies to customers in forward-deployed locations. Some examples of major disruptive events that have occurred include: volcanic ash resulting in partial or total disruption of air traffic, labor disputes halting shipping terminal activities, industrial accidents damaging port facilities, natural phenomenon such as seismic activity, and cyber-attacks or other random computer outages.

Some work on improving and analyzing network resilience is presented in Clark (2017) and Ross (2014). While both use attacker/defender problem optimization to analyze a network's resilience, Ross (2014) adds an optimization model for random hazards, which is similar to our approach to disruptions. Xu et al., (2015) demonstrate possible modelling of the disruptions to a supply chain as an attacker-defender game, in order to prevent large amounts of damage to a military logistical system from a targeted attack.

Findings and Conclusions

We developed six optimization models—five proactive models and one reactive—that strive to deliver items through the supply network to a demand location as quickly as possible. When the network is not subject to disruptions, this problem is a standard network shortest path problem. However, since we are interested in networks subject to possible disruptions, the travel times along the arcs are uncertain. We modeled disruptions as random occurrences with known or estimated probabilities. This assumption is more suitable for a disruption due to natural causes, such as weather than disruption due to interdiction by an adversary. The latter better fits contested situations where strategic, game-theoretic considerations are more appropriate.

We tested our models on a hypothetical scenario that involves a major conflict called Global War 2030, with the major theater of operations in the Philippine Sea. The logistical support in this scenario involves delivery of supplies from Hawaii to hypothetical U.S. installations on the Philippine Islands. The resupplies are shipped through the sea routes and air routes of the theater, from Hawaii through the large port cities of Cebu or Manila, Philippines, and then on to their final destination. All steps of this supply chain use multiple delivery methods, which may have differing times to delivery, risks, or costs of use.

Three different cases of weather patterns, of increasing severity, were used to create disruptions. These cases each presented different results that, when analyzed, provided insight into each model's benefits and drawbacks in dealing with disruptions, as well as their computational complexity and feasibility of implementation. First, the reactive model had one major shortcoming: it assumed that there would be no future disruptions, and so it always used the baseline travel time to find the fastest route through the network. While it made no assumptions about the type of disruptions or their independence, assuming that disruptions would not occur could result in the model choosing a highly risky arc, which could otherwise be avoided. Next, some of the proactive models were too conservative, in that they tried to find routes that avoided any disruptions, even those that caused only minor delays. The best proactive models weighed the pros and cons of taking a route with potential disruptions and would not necessarily try to avoid all disruptions. These effective proactive models generated contingency plans that seamlessly updated the route in real-time in response to a disruption.

Every model examined in this project has strengths and weaknesses that could be relevant to a decision maker looking for an effective supply route in a network subject to disruptions. Though there is not one single best model to use in all situations, all of the models offer different approaches to responding to disruptions and present several alternatives. The decision maker can evaluate the various routes presented by the models and their associated metrics, and make a more informed decision about which model's solution may be the best route for a given situation.

Recommendations for Further Research

First, a more in-depth analysis of reactive model could provide more insight into the exact differences between proactive and reactive approaches. This could be done by analyzing the path taken by each of the different proactive models, given a randomly generated outcome of the network on which the reactive model was simulated. This would provide more concrete information for comparisons between the different models' total travel times despite the different objective functions each one optimizes. Next, we could consider scenarios where the disruption probabilities vary over time, as models that generate detailed contingency plans should excel in these situations.

Lastly, tweaking the reactive model to account for risk to some degree, as the reactive model has nice properties: it often performs well and is fast to compute. Unfortunately, the reactive model can also perform very poorly in situations where it ignores likely and significant disruptions. Consequently, any modifications that would limit these significant downsides in the reactive model would be very beneficial.

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NPS-19-N068-B: Leverage Optimization Artificial Intelligence (AI) to Optimize Global Material Distribution

Researcher: Dr. Ying Zhao

Student Participation: Capt Peter Deschler USMC and Maj Jacob Jones USMC

Project Summary

Given the increased demands on the fleet over ever-larger geographic operating areas, Naval logisticians are increasingly called upon to handle uncertainty, adopt new warfighting concepts of operations, and optimize materiel delivery. Currently, Naval logisticians have to manually coordinate this materiel movement across a vast, complex, and uncertain global material distribution enterprise. The uncertainty of an replenishments-at-sea (RAS) can arise from the vendors, who may not fill specific items on time, or the ships, which may miss the scheduled RAS events because they have to perform different missions from previously scheduled ones—an event that might happen more often in wartime (Phase 2). The complexity of the process can also arise from the differences among various phases of war: for example, some Naval ships' missions, such as humanitarian assistance missions, only happen in peacetime (Phase 0 or Phase 1), while some missions are solely performed in wartime.

We showed how to apply the machine learning (ML)/artificial intelligence (AI) method to compute the cascade effects of logistical uncertainty resulting from item associations and demand networks, by mining customer order tracking (COT) data from combat logistic officers (CLOs), master consumption data, recipes, and breakout (form 1282) and production (form 1090) data from a customer ship—one that needs the services of combat logistics force (CLF) or needs push logistics for food service. Our hypotheses were confirmed in that we were able to design an automation and optimization AI to improve an existing logistics tool, the Battle Load Tool (BLT), in the realm of food service.

This ML/AI method was able to improve the BLT's food service system by more accurately predicting the quantities of each food item to push for future RAS events.

Keywords: *combat logistics force, CLF, replenishments-at-sea, RAS, push logistics, prediction, uncertainty*

Background

We hypothesized that AI technologies would be beneficial in Naval operations for conducting large-scale automation and optimization of materiel delivery and may generate better solutions than human logisticians are able to manually devise. Based on this hypothesis, our long-term goal is to apply ML and AI to assist logistics warfighters such as CLOs, in order to automate and improve the performance of their tasks, and to reduce their cognitive burden in supporting the logistics of complex warfighting scenarios.

The research questions were as follows:

- Of those factors that a CLF's CLOs need to consider when prioritizing and coordinating an RAS, which can usefully be instantiated in an automated tool?
- Which cognitive and ML/AI tools are currently mature enough to prioritize and coordinate materiel delivery?

Findings and Conclusions

To answer the research questions, we first visited the CLF at the 7th fleet, and learned about the current processes, important factors, and challenges in the complex enterprise of Navy global materiel distribution. We discovered that the CLF and CLOs in 7th fleet needed to implement real-time in-inventory visibility (i.e., what inventory is available when) and real-time in-transit visibility (i.e., where inventory is located). We found out that the Navy has two databases that contain afloat inventory visibility: The Force Inventory Management Analysis Reporting System and One Touch. Also, the U.S. Transportation Command has databases that can be used for in-inventory and in-transit visibility. Another need identified by the CLF in 7th fleet, CLOs, and the Global Stock Center was the ability to predict short-term and long-term push/pull demands. Under a pull supply chain, the process of manufacturing and supplying is driven by customer demand, whereas under a push supply chain, the logistics are driven by long-term projections of customer demand. The required prediction and optimization in a push logistics concept typically face particular uncertainty: for example, if a scheduled customer ship does not show up to an RAS event because her mission changes, the whole order has to be canceled, and the order quantity of the next push or RAS for the ship needs to be adjusted accordingly.

To address this uncertainty, we focused on applying ML/AI technologies such as exploratory analysis and visualization, pattern discovery, anomaly detection, Lexical Link Analysis, and causal learning to the push logistics concept and requirements in the context of the BLT—in particular, the task of food service. The BLT is used by a CLO representing a ship to place orders: it generates a Military Standard Requisitioning and Issue Procedures to place an order either to a supply premier vendor or CLF. BLT has been tested in Naval exercises for a few carriers, a few time periods, and a few locations. The previous RAS and general statistics from the BLT consumption data therefore provided an initial estimate of how much to push.

We visited a carrier food service organization to identify the factors and uncertainty conditions that might be needed for more accurate push logistics—for example, the methods of data collection and calculation

of the acceptability of items (i.e., the percentage of the population who would buy a food item), the actual portion prepared, and the portion of the food left over. Uncertainty may be caused by recipe change, ingredient change, breakout (i.e., amount of an ingredient needed based on a recipe; manual division of packaged ingredients may result in a different amount each time), and production variations.

We further worked with the 7th fleet to identify the uncertainty factors in logistics support patterns with respect to an RAS specifically—for example, uncertainty factors related to the large number of vendors, wide geographic area, variable lead times, and complex schedules in the 7th fleet area. The COT data from the 7th fleet CLOs included all the information related to support patterns and uncertainty factors. We then applied techniques such as causal learning, counterfactuals, and LLA to pin down the true cause and effect variables driving fluctuations in demand that must be anticipated under push logistics. The resulting AI system confirmed, in full, our original expectation and prediction that ML/AI algorithms have the potential to automate Naval logisticians' task and optimize global materiel distribution. Our results will benefit Navy operations related to the total Naval logistics enterprise—supply, health services, maintenance, transportation, engineering, and finance. Furthermore, the automation and optimization AI designed for push logistics in food service can be used in other areas, such as the parts service to improve the overall logistics readiness of Naval operations.

Recommendations for Further Research

Given our results, we recommend to test, simulate, and perform data analysis with respect to the design of the automation and optimization AI for push logistics. We also recommend continued research on designing automation and optimization AIs for the other needs we identified in our work.

NPS-19-N118-A: Unmanned Surface Logistics Concept of Support

Researchers: Dr. Douglas MacKinnon, CAPT Jeffrey E. Kline USN Ret., and Dr. Jeffrey Appleget COL USA Ret.

Student Participation: LT Edward Crapino USN

Project Summary

Logistics support plays an essential role in the United States Navy's success at sea, as fuel, food, and equipment are delivered to underway ships on a daily basis via the Combat Logistics Force (CLF). However, with the advent of unmanned vehicle technologies, unmanned logistic surface vehicles (ULSVs) have the potential to provide a less costly and more efficient alternative to conventional CLF ships. Additionally, ULSVs have the potential to enhance freedom of maneuver and lethality in contested environments as they require little to no human intervention during transit. The ability to maintain communications is critical to ULSV operations, especially in a communication-challenged environment such as the Philippine Sea. Through review of literature and experimentation via wargaming, this research proposes an additional or alternative communication architecture onboard ULSVs by exploring the impact of tactical wireless mesh networks (WMN) in communication-challenged environments.

Keywords: *unmanned surface vehicle, USV, unmanned logistics surface vehicle, ULSV, tactical mesh networks, wireless mesh networks, WMN, directional antenna, ultrawideband sensor network, UWB, data flow, logistics, communication architecture, Maritime Unmanned Navigation through Intelligence in*

Networks, MUNIN, tactical airborne network, TAN, wargame, Lightweight Interstitials Toolkit for Mission Engineering Using Simulation, LITMUS, Unity, Combat Logistics Force, CLF, Philippine Sea, communication-challenged environments

Background

By studying and conducting operational testing of large unmanned container ships, organizations such as the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project, were able to provide publicly available documentation concerning communication challenges that ULSVs potentially face during maritime operations. These challenges are further increased in contested areas such as the Philippine Sea, as China has placed great emphasis on the development of cyber and electronic warfare units to support its maritime expansion (Office of the Secretary of Defense, 2018).

For this reason, this research explored alternative ways to maintain data flow that may be less prone to cyber-attacks and more localized. Our results suggest that this may be achieved through the use of directional antennas, ultrawideband (UWB) sensor networks, and range augmentation using tactical airborne networks (TANs) and the Defense Advanced Research Projects Agency's (DARPA's) Towed Airborne Lift of Naval Systems (TALONS). The main attribute of directional antennas is that they have a preferential direction, therefore granting more powerful communication capability over omnidirectional antennas (Kim & Ko, 2005). This was demonstrated during Space and Naval Warfare Systems Command's (SPAWAR) tests of its Directional Ad Hoc Networking Technology (DANTE) antenna in 2010, which achieved a maximum link range of 58 nautical miles (Meagher et al., 2011). As these antennas must be directed (Zhang, et al., 2006), a UWB transmission system may provide an optimal localization method, due to its low probability of detection and high location determination accuracy (Zhang et al., 2006).

TANs may potentially extend the range of ULSVs to other nodes by allowing air assets to exchange data with the ULSVs, or to serve as relay nodes via their own directional antennas. Another alternative is through the use of TALONS. TALONS is a system that enhances intelligence, surveillance, and reconnaissance communications onboard naval ships. During DARPA's 2016 demonstration, TALONS was able to extend the ship's surface-track radar by 500 percent and triple the range of a handheld omnidirectional radio onboard (DARPA, 2016). This research theorizes that TALONS could potentially achieve similar results in tactical WMNs through a robust communication architecture integration.

Findings and Conclusions

As the main focus of this work is the operational feasibility of the proposed communication architecture, we used one of the OA4604 (Wargaming Applications) unclassified sponsored wargames as the basis for our experimentation. Through the use of Lightweight Interstitials Toolkit for Mission Engineering Using Simulation (LITMUS) and its associated Unity engine, Red and Blue teams executed their respective missions to determine optimal ways to implement ULSVs by Blue forces. The proposed communication architecture consisted of SPAWAR's DANTE, UWB sensor networks, TANs, and TALONS onboard the ULSVs and selected friendly units.

One of the key findings is that the proposed tactical WMN architecture demonstrated gave Blue a tactical advantage over Red through an increase in Blue's situational awareness via TALONS and SPAWAR's DANTE antennas. SPAWAR's directional antennas also allowed the ULSVs to be controlled at a large distance.

To note, it was assumed that any loss of communication or data link from and to the ULSVs would trigger the ULSVs to conduct an emergency stop as proposed by the Maritime UK MASS Code of Practice (2018). For this reason, it was imperative to maintain communication and data links with the ULSVs, as the loss of either one would require technical support from nearby friendly units.

Recommendations for Further Research

Considering that our experimentation was conducted at the unclassified level via LITMUS and Unity, much of the results and data acquired were operationally driven with a number of assumptions and technical limitations at hand. We believe that field experimentation involving the proposed communication architecture used in the wargame should be conducted to gain better insight into the system's potential technical flaws. Due to the classification level of the wargame, we recommend conducting similar wargames with similar scenarios at higher classification levels to obtain more accurate data based on U.S. and our adversary's capabilities.

Cybersecurity onboard ULSVs in a tactical mesh network should also be researched in more depth given the potential cyber threats that ULSVs may encounter. Aside from field experimentation, we recommend developing different plugins for LITMUS and Unity that allow adversarial units to conduct cyber-attacks. Alternative communication methods, such as through the use of lights and visual signals from ULSVs, should also be explored.

Finally, the proposal to weaponize unmanned vehicles, as put forth by the U.S. Navy's surface warfare director earlier in 2019, suggests installing combat and weapons systems onboard ULSVs (Larter, 2019). Via field experimentation and wargaming, we recommend researching the feasibility of ULSV weaponization to analyze its impact on fleet tactics. Considering that weaponizing ULSVs may increase the probability of adversarial targeting, deceptive operations similar to the Russian Club-K missile container system should also be researched (Stott, 2010).

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NPS-19-N120-A: Supply Chain Vulnerability Identification Using Big Data Techniques

Researchers: Dr. Douglas MacKinnon, Dr. Ying Zhao, and Mr. Glenn Cook

Student Participation: Capt Peter Deschler USMC

Project Summary

Marines operate the MV-22 globally with support from a multi-tiered maintenance and supply system. However, low aircraft readiness levels demand improved optimization of the current MV-22 sustainment system. With diverse datasets being generated across the MV-22 sustainment system, the data environment is ripe for the application of big data analytics (BDA), which has emerged as a discipline for deriving value from large heterogeneous data environments. This research specifically examined maintenance data for MV-22 aviation depot-level repairables (AVDLRs) that demonstrated high levels of reliability-related demand from 2016 to 2018. A cross-industry standard process for data mining (CRISP-DM) was employed with the application of quantitative methods of analysis. First, outlier demand behavior for three AVDLRs was identified across aircraft, squadron, and serial number, with the use of Tableau. Second, popular, emerging, and anomalous failure themes contained within maintenance comments assigned the same malfunction code were differentiated using Lexical Link Analysis (LLA). Third, classification models were tested for predicting the intermediate-level (I-level) action taken codes (ATC) and program level failure modes, incorporating LLA comment classification categories as an additional independent variable. The findings of this research illustrate opportunities to derive deeper understanding of AVDLR failure and repair across multiple levels of naval aviation maintenance.

Keywords: *big data, BD, big data analytics, BDA, business analytics, business intelligence, lexical link analysis, LLA, MV-22, aviation depot-level repairables, AVDLR, data mining, aircraft maintenance, MRO, predictive modeling*

Background

In response to the Independent Readiness Review of the MV-22 in 2016, a comprehensive effort to improve MV-22 readiness began (United States Marine Corps [USMC], 2019). With the Office of the Secretary of Defense recently setting an aggressive 80% target readiness goal, a significant leap is required from the historical 55% plateau (USMC, 2019). In order to achieve the target readiness goal, the maintenance, repair, and overhaul (MRO) operations supporting the MV-22 must be optimized across the enterprise. With MV-22 aviation MRO involving large amounts of heterogeneous data, opportunity exists to exploit the benefits demonstrated in the commercial sector with BDA.

Findings and Conclusions

This research specifically investigated three related issues that impact MV-22 aircraft readiness. First, delays in detecting outlier patterns of behavior unnecessarily increase maintenance hours and component demand. Second, readiness can be degraded by delays in determining the true cause of failure for components. Third, inefficiencies across the three levels of repair, organizational-level (O-level), intermediate level (I-level), and depot-level (D-level), delay component repair and corrective action.

These issues formed the basis of the three research questions explored in this research:

- How can BDA be applied to improve detection of outlier behavior impacting reliability related maintenance on MV-22 AVDLRs?
- How can BDA be applied to improve true causes of failure determination of trending MV-22 AVDLR component failures?
- How can BDA predictive modeling be used to enhance repair chain efficiency and failure mode determination on MV-22 AVDLRs?

A cross-industry standard process for data mining (CRISP-DM) was employed in order to answer each of the three research questions, and historical fleet-wide O-level and I-level maintenance data from 2016-2018 was collected. Three components that demonstrated the highest reliability-related demand became the focus of the investigation: the Coanda Valve (Part No. 901-363-203-105), Centerbody (Part No. 2311095-1), and Constant Frequency Generator (CFG) (Part No. 766101A). The models and findings to each of the three research questions are summarized separately below.

Outlier Detection

For the top three components, outlier detection modeling was applied to time series demand data, in order to identify outlier behavior according to component serial number, aircraft bureau number and squadron. The value of the outlier detection analysis conducted in this research does not reside in the identification of specific historical findings, as much as the illustration it provides of potential opportunities missed. If Material Maintenance Control Officers (MMCOs) at the squadron level could receive near real-time benchmarking of their maintenance behavior against fleet averages, down to the individual component level, they could approach troubleshooting with greater knowledge. This in turn could drive down unnecessary component replacements, saving time, money and increasing readiness. The potential utility of such benchmarking becomes even more valuable when considering the actual flight hours for each component onboard the aircraft, rather than just demand-based analysis as completed in this research. While troubleshooting an unfamiliar gripe, the MMCO would be equipped with real-time knowledge of the expected lifecycle for all components in the system.

Cause of Failure Differentiation

Malfunction (MAL) codes are assigned when a component is removed and provide a generic description of the type of failure that occurred (Department of the Navy [DoN], 2017). However, MAL codes only provide a starting point when assessing the cause of component failures in order to determine program level corrective actions. To assist in differentiating themes of failure contained within records assigned the same MAL code, Lexical Link Analysis (LLA) was applied to both the O-level description of the component failure, and the I-level description of the corrective action taken. LLA is a text mining tool that creates a network of clusters from words and word-pairs, and identifies popular, emerging, and anomalous themes found in the data (Zhao et al., 2016). LLA was applied to select MAL code groups for each of the targeted three components in order to differentiate themes contained within the maintenance

comments. These findings suggest that LLA could be used to enhance engineering investigations into critical components by identifying primary, secondary, and anomalous themes of failure contained within maintenance comments.

Predictive Modeling

This research sought to determine if I-level maintenance actions could be predicted by O-level maintenance data, and if program level Army Material Systems Analysis Activity (AMSAA) failure mode determinations could be predicted by O-level and I-level data. Overall, the predictive models produced mixed results. When they performed well, it could largely be attributed to the uniformity of the datasets. Further refinement of the models with larger datasets is necessary before operational application. Additionally, the inclusion of the LLA comment classification for the O-level and I-level comments did not enhance the predictive ability of the models. One notable exception was observed for the CFG AMSAA Mode classification. The LLA cluster classifications improved the accuracy of the AMSAA Mode prediction for the CFG, with LLA cluster 4 becoming the most strongly associated variable to AMSAA Mode 34 “CND Suspect Intermittent.” This finding suggests that machine learning algorithms for text analysis could be useful in uncovering valuable information in maintenance comments in the future.

Recommendations for Further Research

Analysis that incorporates D-level and original equipment manufacturer level repair data is a logical next step from this project, and cause of failure differentiation at the program level should consider the actions of these entities. Additionally, the inclusion of engineering investigations, quality discrepancy reports, and even direct built-in-test data from aircraft would enhance the comprehensiveness of further research. Investigation into how LLA theme differentiation impacts the time it takes to understand component failures, and determine the appropriate corrective response, should also be conducted. While this research suggests that LLA could improve the process, it remains to be empirically demonstrated. Additionally, incorporating the human element of maintenance should be researched as a variable influential on aircraft readiness. As suggested by Fisher and Champaigne (2018), BDA could also be utilized to identify the specific impact maintainers have on readiness. Therefore, future research could leverage BDA to detect errors in maintenance data across the fleet, in order to enhance the integrity of the datasets being utilized. Finally, the methodology employed in this research could be expanded across other aircraft systems.

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NPS-19-N123-A: Optimized Transit Tool & Easy Reference (OTTER) Improved Data Analysis

Researchers: Mr. Brandon Naylor and Mr. Alan Howard

Student Participation: No students participated in this research project.

Project Summary

The Optimized Transit Tool & Easy Reference (OTTER) program is a simple Excel tool designed to help United States Navy (USN) surface ships reduce their fuel consumption during transits, while still adhering to mission and operational requirements. Possible fuel savings are a function of not only a ship's mission, but also the base case transit speeds and operational behaviors to which the optimized transit solution is being compared, and the operational constraints that limit the potential optimizations such as keeping multiple engines online for enhanced maneuverability. This research expands on previous efforts by considering a wider range of possible transit scenarios for cruisers and destroyers. Our methods included modeling transits with an average speed ranging from 8 to 27 kts, with up to four hours per day dedicated to running drill sets, where operational conditions included unconstrained engine modes and, at minimum, ships maintaining split plant. In all cases, OTTER improved fuel efficiency compared to the base cases, but the improvements ranged from significant to negligible depending on specific operating and transit conditions.

This effort also solicited feedback on the OTTER's interfaces and training materials via interviews with Navy Surface Warfare Officers (SWOs) at the Naval Postgraduate School (NPS). Interview results revealed ways the OTTER interface can be improved to alleviate confusion, and how to make the training materials more effective. Input from these SWOs will be used to improve the effectiveness of future versions of OTTER and its related materials once it reaches the users.

Keywords: *fuel, logistics, Optimized Transit Tool & Easy Reference, OTTER, transit, surface fleet, refuel, TFP, transit fuel planner, BOSC, Battlegroup Optimum Speed Calculator, SECAT, Ship Energy Conservation Assistance Training, DFM, diesel marine fuel, engine mode, plant configuration, optimization, tools*

Background

OTTER is a tool originally developed by LCDR Warren Blackburn and Mr. Brandon Naylor (Blackburn, 2016) to help ships save fuel, using the mixed-mode fuel optimization method (US Patent No US8050849B1). Past Naval Research Program-funded research efforts into this topic (Howard & Naylor, 2017, Howard & Naylor 2018) produced promising results, but did not have the benefit of working with actual ship transit records. This study intended to fill the gaps in the previous research efforts and theses in part by addressing the inconsistencies in the original transit data, and also model a wider variety of realistic transit conditions by working with students with operational experience who provided real-world "lessons learned." This study was also designed to reveal how OTTER might be made more effective and how user error of the tool might be reduced. While it was expected that OTTER would provide fuel savings, and this would always be an improvement on the base case transit behaviors, it was also assumed the fuel savings would vary greatly depending on operational conditions.

Process and Methodology

This study was conducted by modeling a wide variety of transit conditions in OTTER with various operational constraints and requirements, in order to determine how much fuel could be saved by using OTTER transit solutions versus base case transit behavior. Over 650 transits were modeled for cruisers and destroyers with Plan of Intended Movement (PIM) window speeds ranging from 8 to 27 kts, with up to four hours per day diverted for training exercises. These operating conditions allowed and prevented the use of the trail shaft engine configurations; ships using high speeds to maintain position at the front of the PIM window were modeled as base case conditions.

Additionally, we recruited SWO volunteers from the NPS community to gauge the effectiveness of the training materials and determine how the interface might be improved. These volunteers were given a copy of OTTER with the included instructions, and asked to try to model several transits and comment on their experience. Through their feedback and observing the experience of a new user, we learned how the training materials can be improved, noted changes which could make the user interface more intuitive, and discovered a bug in the interface.

Findings and Conclusions

This study found that OTTER's optimized transit solutions could produce significant fuel savings for cruisers and destroyers, even in cases where operational conditions required significant diversions or restricted engine configuration. Typical OTTER fuel savings were around 10% for unrestricted transits and 8% for transits that did not allow use of the trail shaft configuration. While the vast majority of transit conditions would likely produce fuel savings ranging from 3% to 15%, in extreme cases, OTTER could produce savings as high as 20% or conversely, offer negligible advantage over the base case.

While OTTER was well-received by the volunteer SWOs who tested the program, their feedback made it clear that the OTTER tool and training materials can be improved. Suggestions included making the instructions and training materials more consistent with the rest of their training; in addition, the SWOs also uncovered a bug in the interface that allowed the user to edit a protected value. Their feedback will be incorporated in future versions of OTTER.

Recommendations for Further Research

This study has demonstrated that adopting OTTER across the fleet could result in significant fuel savings. However, further study is needed to facilitate this adoption, and to assess the impact OTTER's fuel savings could have on logistics and operational readiness. Once the recommended improvements from this study are made to OTTER and its training materials, further work will also be required to test OTTER in an operational environment, compare actual fuel savings against the model, and verify that the improved training materials are effective. This work will support the eventual adoption of the OTTER tool and represents a possibility for huge cost savings and increased operational capability.

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NPS-19-N176-A: AoA Paradigm for Early Visibility of Logistics and Cost in the Acquisition Process

Researcher: Dr. Moshe Kress

Student Participation: No students participated in this research project.

Project Summary

Analysis of Alternatives (AoA) is a study comprising a crucial part in the process of acquiring a new system for the DoD. AoA is a multi-dimensional decision process that involves several criteria and stakeholders. There are three sets of criteria according to which alternatives are evaluated in an AoA. In most studies, typically, two of the three sets— effectiveness criteria (what can the system do and how its capabilities fit the operational requirements) and cost criteria (acquisition and lifecycle cost)—draw most of the attention. The third set, usually given less attention in an AoA, is concerned with long-term readiness and sustainment implications.

Our research focuses on this third set of criteria, and has two goals: (a) study the set of criteria related to readiness and sustainment, and define measures of effectiveness (MOEs) that help evaluate these criteria, and (b) develop an aggregation process that transforms the MOEs values of the alternatives into a single relative value. In this research, we study in detail the criteria that affect the long-term viability and usefulness of an alternative, which determine readiness and sustainment, and propose an analytic framework for evaluating the relative merit of alternatives with respect to those criteria.

Keywords: *Analysis of Alternatives AoA, readiness, sustainment, Data Envelopment Analysis, DEA*

Background

The DoD Acquisition System comprises three interconnected stages that start with specifying requirements: a procedure called Joint Capabilities Integration and Development System. The second stage, called the acquisition process, determines appropriate materiel solutions for the requirements. The third stage is concerned with funding and financial-controlling activities contained in the planning, programming, and budgeting execution process. Most of the decisions that have long-term sustainment, readiness and logistics implications are taken at the second stage, where materiel choices are made. The overarching process dominating this stage is the AoA, which in general, trades off the effectiveness of a materiel solution with its risks and costs. The AoA in the acquisition process is essentially a large-scale multi-criteria decision analysis (MCDA) problem that involves multiple stakeholders and many uncertainties. The set of criteria used in evaluating alternatives, and their weights or importance, depend, among other factors, on the availability of the aforementioned alternatives.

For example, the risk associated with acquiring an off-the-shelf system is considerably lower than the risk in developing a new system. Thus, the “risk” criterion, with all its derivatives, is less prominent for the former than the latter.

In this study, we focus on systems that are still in various stages of development, which means that the AoA process is typically not a “one-shot” decision event, but rather a sequence of decisions marked by milestones. In these settings, the AoA starts off with a set of potential alternatives being developed as prototypes. As time passes, data is collected and information is gained with respect to each contending alternative. Each milestone in the research and development (R&D) phase involves solving a MCDA problem that determines which alternatives continue to be relevant, and therefore continue in the R&D phase, and which alternatives are dominated, and therefore deleted from further consideration. The process culminates in a winning alternative.

The purpose of this research is to define the criteria relating to readiness and sustainment, and develop a model that aggregates evaluations regarding these criteria. The new paradigm may facilitate better (and earlier) awareness to sustainment considerations, readiness implications, and total ownership cost during the acquisition process.

Findings and Conclusions

The readiness of a system has three different aspects: technological, technical and functional. Technological readiness describes the state of a system while still being developed, while technical and functional readiness relate to a system when it is fully operational and already deployed. Our study focuses on the latter two aspects of readiness. A system is technically ready if all its components are in a perfect working condition, and functionally ready when its supporting resources, such as infrastructure, energy, communication, and personnel are available and functioning.

We find seven MOEs for evaluating an alternative with respect to readiness and sustainment:

Mean Time Between Downs is a combination of the mean time between failures and the mean time between regular services. The former is a probabilistic parameter and the latter is typically a deterministic parameter specified by the manufacturer; we propose a formula for estimating this parameter.

Mean Down Time is calculated as a combination of down time following a failure, and regular scheduled service time. We propose a formula that combines the deterministic (scheduled service) and probabilistic (failure repair) time parameters.

Maintenance Cost is comprised of fixed costs of infrastructure (e.g., shops, storage facilities, labs, equipment, personnel) and variable cost (e.g., replaceable parts, energy); we develop a formula for estimating this cost.

Operational Cost covers the actions needed for operating the system. Such a set is typically well defined, as it establishes the foundation for functional readiness. This cost is measured by the number of operators and controllers, broken down by required skills, cost of operating facility (when applicable) and the amount and type of energy and supplies needed for the operation.

Interdependency is a crucial, yet elusive, characteristics. The more a system depends on other systems, the more it is vulnerable to possible breakdowns and failures of those peripheral systems. We develop a new MOE for measuring the impact of interdependency.

Personnel is mentioned in the Operational Cost mentioned above; however, we also need to take into consideration the sensitivity of the alternative system to staffing. The latter includes the number of personnel and their skill set, and we propose a new measure for this factor.

Supply chain (SC) is affected by many factors, which can impact its robustness and how it supports a system. However, the literature has not reached a consensus on how to measure its impact. We propose using an ordinal scale for ranking the alternatives according to the impact of the SC.

Next, we develop an aggregation process based on data envelopment analysis (DEA). DEA has been applied to hundreds of application areas including several DoD-related applications such as evaluating the efficiency of air-force maintenance units and US Army recruitment centers. DEA is a non-parametric methodology for comparing multiple entities, which use several inputs to produce several outputs. In the full technical report, we give more details about the methodology and demonstrate its effectiveness on an example.

Recommendations for Further Research

The methodology described above could be applied at any stage of the AoA, and expansion of this work is worthwhile. Obviously, as the development process of an alternative progresses, more information and data are available, and thus the evaluations become more robust and significant. However, we recommend initially implementing our methodology as an ongoing AoA study; after some feedback, the number of MOEs could be expanded by breaking down the factors to sub-factors, creating a hierarchical structure similar to the Analytic Hierarchy Process. Further research could also take data from an implementation and analyze its impact.

NPS-19-N180-A: Effects of Environmental Factors on Additive Manufactured Materials

Researchers: Dr. Claudia Luhrs and Dr. Troy Ansell

Student Participation: LT Josh Ricks USN

Project Summary

The emergence of additive manufacturing (AM) as an approach to generate parts is changing the way our industries operate, and is shifting our mindset regarding procurement, distribution, and supply networks. The use of AM technologies is expected to increase the supply chain proficiency and lower costs. However, those benefits can only be realized if the materials produced reach their anticipated lifecycle. Thus, with the expanding use of AM approaches for the fabrication of key parts and components for Department of Defense (DoD) applications, there is also a growing need to identify the factors that could put the predicted advantages of the technology at risk. Knowing which variables could affect the lifetime of an object will allow stakeholders to use realistic estimates in terms of when to order new supplies.

The literature in regard to the mechanisms that three-dimensional (3D)-printed materials suffer as result of environmental attack is scarce, thus, this study attempted to address such deficiency. The research conducted aimed to determine the effects that humidity-, ultraviolet (UV) light-, and salt-containing environments have in the composition, microstructure, and properties of the most common materials used for 3D printing of parts.

Keywords: *additive manufacturing, 3D printing, environmental degradation, marine environment AM*

Background

The use of AM techniques to produce parts has grown exponentially in recent years; in fact, the technology has the potential to become the standard manufacturing process for many polymeric parts and for selected metals/alloy components. Multiple research groups are already addressing the challenges identified in recent years for the wide adoption of AM fabrication, from basic understanding of the process and material evolution during the layer-by-layer deposition, to complex parts design, post-processing steps, certification/qualification, and repair strategies. However, despite the widespread attention that AM has received, and the advances made regarding the accuracy and reliability of the equipment and processes, we noticed that information regarding how the raw materials and the 3D-printed parts will age or degrade due to environmental factors is extremely limited.

As mentioned in the abstract, the emergence of AM fabrication routes as a new approach to generate parts is changing the way our manufacturing industry operates. Thus, information about how environmental conditions will affect the materials useful life and performance should be available to stakeholders. The work conducted fits very well with the mission and objectives of the sponsor's portfolio. Material scientists/engineers and supply chain/logistics specialists are some of the groups that could benefit from the study, since the data generated could provide a better prognosis of materials cycle life.

Hypothesis: Subjecting 3D printed materials to accelerated weather testing will allow us to determine if, and to what extent, the environment affects the properties of materials used for 3D printing and those of the objects produced.

The research questions that the study helped answer include:

- Are the raw materials used to 3D print parts going to suffer changes in dimensions, composition, or properties due to environmental factors?
- Which environmental factors will have a major impact on materials' properties?
- If there are changes in properties, are those large enough to compromise the material performance?
- Which materials will be more susceptible to environmental exposure?

Findings and Conclusions

An accelerated weather tester was used to perform aging treatments in 3D-printed polymers and composites. Each environmental cycle was a week long, and alternated four hours of UV exposure with four hours of a dark, humid environment. Different polymers, including polylactic acid (PLA), glycol modified polyethylene terephthalate, acrylonitrile butadiene styrene (ABS), and nylon and their composites were studied. For the steel studied, a salt fog chamber was employed to expose tensile specimens to environments that simulate conditions similar to marine environments. For the polymeric and composite samples, optical and electron microscopy were employed to assess the changes.

The changes in mechanical properties of the as-printed (AP) and heat-treated (HT) materials after environmental exposure were analyzed using tensile and hardness testers. For the alloy under study, the chemical and microstructural features after controlled exposure to environmental factors were also identified using a scanning electron microscope, coupled with energy dispersive spectroscopy.

Based on visual and microscopic examination of the materials, and the mechanical properties of the specimens after exposure, this study identified which polymers and composites are more likely to degrade under the UV and humidity conditions, and which could withstand them. We found that carbon fiber (CF) fillers increased the resistance to exposure while other fillers, such as bronze and steel, reduced it. The mechanical properties of nylon composites remained unchanged after the environmental treatments, while PLA and ABS composites suffered the largest reduction in strength.

3D-printed maraging steel tensile specimens were used as example of alloy behavior and were exposed to corrosive environments using a salt-fog chamber. Samples were used directly in the AP condition and after being heat treated. All samples suffered changes in properties, however, the HT parts showed to be much more susceptible to corrode and present reduced strength. Defects in the prints, such as lack of fusion near the surface, exacerbated the corroding effect of the salt-fog environment on the tensile specimens under examination.

We observed that 3D-printed PLA with CF became brittle after exposure, however, withstood three weeks of UV exposure as opposed to PLA with other fillers, such as bronze and steel, that were too brittle to test after one to two weeks. ABS filled with CF lost some strength upon three-week UV exposure but could be utilized to perform adequately for lower strength applications. Nylon reinforced with CF was the strongest material and showed no significant degradation in yield or tensile strength through week three of UV/humidity treatments.

After 500 hours of salt fog exposure, the mechanical properties of 3D-printed maraging steel are changed: Samples printed in 45 direction and heat-treated at 600° C saw a 5.8% decrease in strength. Samples printed in Z direction with no HT showed a 0.57% decrease in strength. Corrosion-induced degradation in tensile properties was greater in maraging steel samples which were heat treated. HT samples saw a 4.3% degradation after exposure as compared to a 2.2% degradation in non-HT samples.

Recommendations for Further Research

Based on our findings, awareness of an individual AM material's resistance to environmental attack could be promoted, along with selecting the best material for specific jobs.

NPS-19-N181-A: Security Gaps of Husbanding Service Providers (HSPS) and Viability of HSPS in Major Theater Conflict

Researchers: Dr. Geraldo Ferrer and Dr. Simon Veronneau

Student Participation: LCDR Clifford Rivera USN, LCDR James Steele USN, LCDR Long Tran USN, LCDR Malcolm Elliott USN, LCDR Shannon Percival USN, and LT Jonah Petrinovic USN

Project Summary

Maintaining a forward-deployed presence world-wide is integral to the mission of the Department of the Navy (DON). To conduct port visits, the Navy uses a network of organic and contractor-furnished assets supplied by foreign companies to provide husbanding services, and coordinate delivery of supplies at various ports where organic footprint does not exist. To assess the implications of using husbanding service providers (HSPs), this research had three objectives: Evaluate the use and demand for HSPs in peace time during routine operations and during a potential contingency, assess the security vetting of HSPs, and estimate the Operational Security (OPSEC) implications and potential for exploitation by likely adversaries. To better secure the force before, during, and after port visits, three alternative courses of action (COAs) are proposed to improve the current operational posture.

Keywords: *Operational Security, OPSEC, husbanding service providers, HSPs, Naval Supply Systems Command, NAVSUP, overseas deployment, contingency operations*

Background

Naval Supply Systems Command (NAVSUP) contracts services for the Navy, Military Sealift Command, Army, and Coast Guard vessels conducting port visits in non-U.S. supported ports. Presently, there are six regional multi-award contracts (MAC) in place that provide worldwide husbanding services, in each area of responsibility (AOR). Under the MAC, many potential suppliers have fair opportunity to bid for a task order awarded for each ship's port visit requiring husbanding services (NAVSUP, personal communication, February 15, 2019). Sound OPSEC practices are important to maintain security and freedom of movement of U.S. forces. Subsequent screening of subcontractors is an important link for maintaining security of operations. Vendor vetting is important to reducing risk in conducting business with third-party and foreign-national logistics providers. Weaknesses in the processes by which contracts and task orders are awarded, and shortfalls in contractor oversight and payment processes, have been the subject of review by the DON (Naval Audit Service, 2014). Sensitive information passed to HSPs during port-visit coordination presents a vulnerability in security of the U.S. Navy. The Glenn Defense Marine Asia corruption case (Whitlock, 2015) demonstrated the DON's vulnerability in contract management by exposing how HSPs can influence key personnel and compromise OPSEC in theater (Burke, 2013). That incident highlights how easily ship schedules can be manipulated or compromised to benefit an HSP. It also reveals the risks and uncertainty associated with security when working with foreign third-party vendors. Furthermore, during a time of major theater conflict, the logistical challenges of relying exclusively on HSPs can quickly mount to the point where port visits are no longer feasible, compromising the U.S. Navy's mission. Properly compiled, the information passed on to these contractors can provide insight to the type of mission and readiness of the fleet in theater.

Findings and Conclusions

This research directly answers the need from OPNAV N4 to investigate the OPSEC considerations of HSPs and their implications for the entire spectrum of the naval forces deployed overseas. It fills a need to evaluate the consequence of using foreign HSPs supporting our fleet worldwide.

This study followed a multimethod field study methodology, combining literature review of unclassified and classified resources and archival data analysis, as well as semi-structured interviews of subject matter experts. We have high confidence in the reliability of the information and data obtained as part of this process. Two groups of students used these methods to complete two separate master theses (Elliott, Percival & Steele, 2019; Petrinovic, Rivera & Tran, 2019). We have combined results of these theses and augmented them with our own interviews and document reviews.

This research found that there is not a standardized robust security vetting process in place for conducting business with HSPs (NAVSUP, interview conducted with authors, March 20, 2019). In the absence of a standard vetting process, contracting officers (KO) are making a responsible determination on the HSP as prescribed in Federal Acquisition Regulation Part 9. Vetting HSPs and gaining a true understanding of a vendor's intentions and background is difficult. They are business/service providers that are not necessarily loyal to the U.S. Their priorities will naturally lie with their native country or with simplifying their processes to increase profits. To better secure the force, this research proposed three alternatives to close this security gap:

1. *Maintain Status Quo*: Maintain the current process with an understanding of the associated risks. Combine the responsibility determination made by the KO with the quality assurance surveillance plan conducted by the contracting officer representative (COR), and Port Visit Feedbacks provided by ships.
2. *Expand Security Requirements*: Expand the current vetting process to require prime contractors to disclose the subcontractors hired to fulfill the port visit task order. The subcontractors would then need to meet the same requirements of database representation and performance documentation as the prime contractor.
3. *Implement a Logistics Support Representative Program*: Introduce a fully vetted U.S. government representative to act as a liaison between HSP, COR and customer to handle sensitive information. This program would be implemented sooner in select ports based on corruption and terrorism indicators, and in regions with greater proximity to near-peer threats.

To support operations in a contingency environment, we made several recommendations. Some of them provide multiple benefits to the U.S. Navy, which is why we believe they should be researched in greater depth soon:

1. *Build our own organic capabilities* in the 7th Fleet AOR and in other AORs as needed. These assets would be better equipped to handle a surge in demand that would be beyond the capabilities of HSPs. It would improve security and it would allow prepositioning of assets required for port visits.
2. *Enhance diplomatic relations with host nations* in all AORs, especially the ones that the U.S. military desires to use for port visits during a major theater conflict. Having other countries as allies would allow the U.S. military to use military ports or preposition organic assets would increase flexibility for the US Navy.

3. *Integrate logistics in the annual wargames* to highlight the challenges of pulling into foreign ports. Simulating poor communications and training supply officers to expedite port calls in such environments would increase everyone's resiliency.
4. *Expand the current vetting process* to require prime contractors to disclose the subcontractors hired to fulfill the port visit task order, as described above. Operations security and the safety of U.S. military personnel depends on understanding the backgrounds of those who work for HSPs. A random audit program is an excellent first step to ensure security.

This study contributes to the body of knowledge on the OPSEC considerations of HSPs. It identifies clear COAs to enhance the operational security of our forces when deployed overseas. Short-term implications are that the U.S. Navy still has an important weakness in its HSP program, and that it is necessary to enact long-term structural changes soon.

Recommendations for Further Research

Future research should focus on how such an organic capability could be created to support the U.S. Navy; identifying the costs and the procedures associated with implementing these recommendations should be prioritized.

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NPS-19-N220-A: Low Temperature, Low Cost, Precision Metal Additive Manufacturing (M-AM)

Researcher: Dr. Jonathan Phillips

Student Participation: LT Alexander Roman USN

Project Summary

In this study, our team tested a postulated new route, Reduction Expansion Synthesis: Sintered Metals (RES-SM), to create sintered metal bodies of a designed shape, from powders at ambient pressure, hundreds of degrees below the metal melting temperature. The team succeeded in first stage development,

making solid Nickel (Ni) parts of different shapes from mixtures of Ni and Nickel oxide (NiO) powders, effectively initiating a potential commercial novel Metal Additive Manufacturing (M-AM) technology, as summarized in a US Patent filing, and a peer reviewed publication. It must be understood that this technology is in the “infant stage” and many technical issues, such as hardness and strength of final part, remain to be solved before full development can be pursued. Still, there are apparent major advantages of RES-SM relative to existing M-AM technologies, that could lead to commercialization after further development.

Keywords: *additive manufacturing, metal*

Background

As detailed in a patent filing (Phillips & Daniels, pending) and a published journal article (Daniels, Rydalch, Ansell, Luhrs, & Phillips, 2019), the fundamental postulate underlying this project is that a form of Reduction Expansion Synthesis (RES) can enable technology that produces solid metal objects, rapidly, from powders at ambient pressure, and temperatures far below the melting temperature of the metal. RES is a novel chemical approach to create metal from metal oxides, invented by researchers at the Naval Postgraduate School to make create unique materials including metal particles (Zea, Luhrs, & Phillips, 2011; Luhrs, Kane, Leseman, & Phillips, 2013; Luhrs, Leseman, Phillips, & Zea, 2014), metal thin films (Pelar et al., 2018; Phillips, 2019), and fuel cell (Elbaz, Phillips, Artyushkova, More & Brosha, 2015) and battery (Lee et al., 2018) electrodes.

The basic chemical concept of RES is that some solids, such as urea, release volatile metal radicals upon thermal decomposition. In an inert gas environment these radicals will in turn remove oxygen from nearby metal oxide species. The net result is reduced metal structures are formed from metal oxides, generally in less than twenty minutes in furnace. In order to employ RES to make metal parts a second novel additional chemical postulate was made: The reduction of metal oxide particles, in a mix with metal particles, via the RES process will result in the formation of metal atoms. These atoms will migrate to join existing metal particles. This process is repeated countless times as each oxygen is removed by a reducing radical, producing another metal atom, which bonds with the outer layer of a metal particle. This process eventually leads to the formation of metal ‘necks’ joining pure metal particles together, concomitantly creating a single solid metal object from a particle bed.

Findings and Conclusions

The RES-SM process as designed and tested, is described in detail, and illustrated, elsewhere (Daniels et al., 2019), and consists of the following five simple steps:

One: A ‘mold’, no top or bottom, is created either by laser cutting a shape from hard plastic, or by using a standard (<\$1 K) polymer based AM device.

Two: The mold is placed on top of a sheet of Grafoil, a material with paper consistency made entirely of compressed natural graphite flakes, into which many small holes are punched (e.g. with a pin).

Three: The mold is then hand packed with a mixture of metal and metal oxide particles. Generally, for this first study the mixture consisted of equal weights of ~20 micron scale nickel and nickel oxide particles.

Four: The mold is placed above a bed of urea, or suitable alternative, such that decomposition products can channel through holes in the Grafoil to affect reduction of oxide particles. The mold is removed leaving only the particle compact. The compact is stable, thus can be processed even in inherently unstable environments such as shipboard.

Five: The mold/urea is heated to ~900 C for approximately 20 minutes in an inert gas atmosphere. A single fully metal part is removed upon cooling.

As discovered using scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and x-ray diffraction (XRD), the solid, metal-only, part that forms from the mixture of metal and metal oxide particles via the RES-SM process mimics mold shapes; two shapes tested very well. There is shrinkage, but in a manner similar to all M-AM processes the shrinkage occurs evenly across all part dimensions, hence can be accommodated in design. The final product presents necks, of a few microns' length, of completely reduced metal that connect the original metal particles. It is clear these necks form from metal released from original oxide particles during treatment in the furnace.

The “as produced” parts are similar in properties to “brown” metal parts created using more standard methods M-AM technologies such as Particle Injection Molding. Thus, parts produced using RES-SM require “post-processing” to reach full density and strength. In our study parts were treated by hot isostatic pressing (HIP), the same process generally employed with brown parts in commercial processes. Parts thus post-treated are fully self-supporting, near 100% density, with hardness values identical to those like others reported in literature for traditional fabrication methods, in particular casting.

In sum, RES-SM is a novel chemical approach to M-AM that uses affordable and environmentally friendly precursors, such as urea and metal and metal oxide particles, to create brown metallic parts at moderate temperatures. The process is very rapid relative to alternatives, and employs only relatively inexpensive, non-specialized laboratory equipment. The creation of fully dense parts requires the same type of post-process treatment of the brown parts, such as HIP, employed to process brown parts made using existing M-AM technologies.

Recommendations for Further Research

The following are highly recommended for further research: setting up larger furnace and employing it to make parts using RES that are up to 20 cm in at least one dimension, demonstrating alloy parts can be made, initially working with iron-nickel alloys; testing the postulate that cermets can be made using a variation on the RES protocol; testing the postulate that Titanium metal parts can be made using a variation on the RES protocol; testing postulated methods to increase part, specifically iron and nickel containing materials, density at less than 1000 C at ambient pressure.

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NPS-19-N326-A: Metrics and Measurement in Additive Manufacturing Domain: Adoption and Return on Investment

Researchers: Dr. Amela Sadagic, Dr. Robert Eger, and Ms. Kristen Tsois

Student Participation: LT Gilbert Garcia USN, LCDR Bradford Edenfield USN, LT Kazuma Yoshida JMSDF, and LCDR Joseph Giordano USN

Project Summary

Additive Manufacturing (AM), a technology that allows building physical artifacts by adding successive layers of material, and activities geared towards large-scale adoption of this type of technology have already begun. The Department of the Navy (DON) created an AM Implementation Plan whose ultimate goal is increased readiness, with the capability to engage in rapid development and enhance warfighting capabilities. Successfully adopting AM and using in daily operations is connected with the service's ability to measure its adoption and return on investment (ROI), and the capacity to analyze that information and remove any identified impediments. We designed and executed a set of research activities aimed at creating a comprehensive understanding of the metrics needed to (a) measure adoption of AM technologies, and (b) articulate the value-added and ROI for AM. The work included field visits with naval installations that have AM capabilities, focus groups with AM practitioners, and regular interactions with a range of stakeholders in this domain. The effort also included the design of an AM portal—an infrastructure capable of housing a variety of AM resources, amassing information about AM adopters, and recording activities in the AM domain. The same portal is designed to measure the adoption process and ROI associated with adopter-generated innovations. Our work included a collaboration with other colleagues from the DON to ensure that leveraging of results across the naval domain is fully achieved.

Keywords: *additive manufacturing, AM, technology adoption, metrics, return on investment*

Background

An initiative outlined at the beginning of 2018 addresses the DON's AM Implementation Plan (DON, 2017) and details accelerated implementation initiatives across different domains, with the ultimate goal

of increasing readiness (sustainment), enhancing warfighting capabilities, and enabling rapid development (fielding) (DON, 2018). Measuring both adoption and ROI of AM needs to be integrated into those efforts as well.

Multiple mechanisms enable and expedite diffusion of innovation and adoption of technology in any social group (Davis, 1989; Rogers, 1995; Sadagic, et al., 2015; Venkatesh et al., 2000). Additionally, large-scale adoption of technological innovation provides an opportunity for a paradigm shift and change of how one operates in a given domain (Sadagic, 2008). This type of change also brings a promise of being more productive, and in the case of AM, being able to augment current processes and capabilities while reaching a state of operational readiness that would not be possible otherwise.

The type of change and value that is expected from large-scale adoption of an innovation inevitably requires considerable investments to be made in that domain. These are measured by time investments, but also material, logistical, and human support needed to reach those goals. The process of identifying ROI remains a crucial concern for a performance-oriented approach, not only in business practices but also in the government sector (Chmielewski et al., 2002; Oswalt et al., 2011). We used the lessons learned from past research efforts to look for and advise on mechanisms that bring the elements of self-sustainable process into the fold (Friedell, 2016; Grimshaw, 2017; Sadagic, 2008; Sadagic, 2018). We hope that in the long term, these approaches will help reduce the costs, make AM more affordable for the naval community, and increase its overall ROI.

Findings and Conclusions

Our methodology included the following research activities:

1. Study of literature in the domains of technology adoption, metrics and measurement of diffusion of innovation, and ROI.
2. Field visits to AM laboratories, units that own AM capabilities, base commands, and other institutions relevant to AM activities in the naval domain. Our major goal was to enable face-to-face discussions with colleagues and support our data collection efforts.
3. Collaboration with stakeholders in this domain, including our topic sponsor N4, Naval Facilities Engineering Command, Naval Sea Systems Command (NAVSEA), United States Marine Corps Systems Command, as well as industry representatives.
4. Communication and interaction with domain users (shore installations, ships, and units).
5. Collaboration with Naval Postgraduate School (NPS) and Modeling, Virtual Environments and Simulation (MOVES) colleagues who work on implementing the AM portal.
6. Collaboration with forums and other colleagues who actively work in the AM domain.
7. Analysis of data sets collected in the project.
8. Design of theoretical and methodological principles, and models for measuring adoption and ROI.

As a part of our project activities, we designed Institutional Review Board (IRB) documentation to support our focus group discussions and obtained approval to execute that study from the NPS IRB Committee. We executed the following seven field visits: (1) AM Lab, Camp Pendleton, (2) FRCMA Det. Patuxent River MMCO, Patuxent River, MD, (3) Southwest Regional Maintenance Center, Additive Manufacturing Lab/Mobile Innovation Center, San Diego, CA, (4) Mid Atlantic Regional Maintenance Center, Technology & Innovation Lab, Norfolk, VA, (5) NAVSEA 05D - Integrated

Topside design, Dahlgren, VA, (6) AM Lab, Camp Pendleton, CA, and (7) USS Makin Island, CA. The insights that we gained as well as the data we collected during those visits helped us identify a set of parameters that have a potential to influence both the adoption of AM and ROI in the naval domain. We also designed a model of adoption and ROI, and suggest the categories of AM users and defined their training needs.

The data sets collected during FY19, and our growing understanding of the aspects and characteristics of diffusion and adoption of AM, allowed us to expand and refine the structure of the AM portal. We included elements that are designed to support peer review, recognition of innovators and adopters' efforts, best practices, teaming opportunities, as well as entries that provide account about group events and results (for example, past and future training events organized by AM lab). The same AM portal would allow easy retrieval of data, including the metrics and projected ROI. Our field visits allowed us to identify the issues that get in the way of the adoption process, and propose approaches that can help alleviate or remove these issues, therefore maximizing ROI.

The following students and their thesis topics were supported by this project:

1. LT Gilbert Garcia (USN), LCDR Bradford Edenfield (USN), and LT Kazuma Yoshida (Japan Maritime Self-Defense Force): Establishing an Additive Manufacturing NEC for the Machinery Repairman to Enable Efficient Use of AM and Mass Adoption of the Technology. Advisors: William Hatch, Kenneth Doerr, Amela Sadagic. Students graduated in June 2019.
Thesis document: <https://calhoun.nps.edu/handle/10945/62753>
2. LCDR Joseph Giordano (USN): Capacity and Cost Analysis of Navy Additive Manufacturing. Advisors: Robert Eger, Amela Sadagic. Student is scheduled to graduate in December 2019.

During FY19 we took part in several AM events organized by naval institutions, and gave two presentations:

1. Sadagic, A. (2019). NPS Center for Additive Manufacturing: 3D Scanning, Large Scale Technology Adoption, and More, Digital/Virtual Twin Workshop: 3D Scanning to 3D Data Publishing, Naval Surface Warfare Center, Port Hueneme Division (NSWC PHD), Port Hueneme, CA
2. Sadagic, A. (2019). NPS Center for Additive Manufacturing: Large Scale Technology Adoption, Naval Expeditionary Construction Force (NECF), Additive Manufacturing Stakeholder's Meeting, NAVFAC EXWC, Port Hueneme, CA

Recommendations for Further Research

Technology adoption is process that takes time and consistent effort on the part of all individuals and groups that have a stake in the outcomes connected to effective deployment of that technology. That process is best served if it includes continuous activities directed towards measuring the performance of the global adoption process, follow on activities of each stakeholder over time, and analysis of those results. Data collected in that effort will allow identifying a need to intervene and, in some cases, remove issues that get in the way of future adoption and, in other cases, distribute and deploy positive experiences and practices across adopters. ROI will, therefore, be maximized if there is a tight connection between adoption strategies and service's ability to measure the effects that different strategies produce over time.

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N8 - INTEGRATION OF CAPABILITIES & RESOURCES

NPS-18-N139-A: Retention Analysis Model for Manpower and Personnel Analysis

Researchers: Dr. William Gates, Dr. Sae Young Ahn, Dr. Amilcar A. Menichini, and Dr. Simona Tick

Student Participation: No students participated in this research project.

Project Summary

This report addresses deficiencies in our understanding of service members' career trajectories. The insights generated will be used to construct more sophisticated and useful models of long run manpower projections, allowing complex simulations to predict the impact of personnel policy changes. This will allow Navy leadership to avoid unanticipated shocks to service member supply and quality.

This report proceeds along two lines. First, we collect a dataset of Navy officers and examine their career trajectory, paying particular attention to their educational background and sociodemographic characteristics. Using long-term trend, as well as regression analysis, we find significant retention rate differences over the long run across gender, marital and dependent status, race, and education level. While the long run trends and regression results are illuminating, we should be wary of drawing definite conclusions about the innate ability or desire of officers to stay or separate based on these analyses. Without a formal model to distinguish between correlation and causation, we should recognize that the findings in this study primarily help direct our modeling efforts in subsequent years.

Second, we provide an in-depth description of dynamic programming models, demonstrating their usefulness and internal consistency for predicting rational, forward-looking agents making choices that affect their future. We provide a detailed technical description of the model, defining value functions, Bellman's equations, and other concepts necessary to program, estimate, solve, and simulate a dynamic programming model. We then propose the path forward to examine how service members in different communities may make different career choices.

Keywords: *retention modeling, force structure modeling, retention bonus, reenlistment bonus, logistic regression, retention auction*

Background

The most critical resource of the United States Navy is its personnel. Despite its importance, relatively little is known about the career trajectories of Navy officers. This lack of knowledge is especially problematic for long-term planning and introduction of attempts to attract and retain the best and brightest. Indeed, the Navy has been more reactive, rather than proactive, in enacting personnel policy.

Difficulties forecasting manpower and simulating expected impacts of policy changes in retention rates will be compounded by generational shifts in the sociodemographic makeup of the population, increased competition from the civilian sector, and large-scale compensation changes, such as the Blended Retirement System.

The goal of this report, as well as our first report issued last year, is to address current deficiencies in our understanding of the career trajectories of naval officers. The expectation is that the insights generated in this report will be used as a basis to construct more sophisticated and useful models of long run projections of manpower, allowing complex simulations to predict the impact of personnel policy changes. Navy leadership can then plan further ahead with greater confidence, and not be surprised by unanticipated shocks to the supply and quality of officers.

Findings and Conclusions

In the first report issued for our Retention Analysis Modeling project last year:

- We surveyed the literature for economic theory and econometric models that had been or could be adapted to examine policy levers affecting the reenlistment rates of officers and enlisted sailors. These models included various ad-hoc, average cost of leaving, and dynamic programming models (also known as dynamic retention models or DRMs).
- We found that various econometric problems, such as reverse causality, measurement errors, omitted variable bias, etc., make many of the examined models unsatisfactory for forecasting retention rates in response to policy levers. Policies based on such models could yield outcomes that are greatly different from expectations, requiring further adjustments to correct for such mistakes.
- One candidate model that was recommended for further study was the DRM. One flavor of these models was created by RAND Corp. and has been used since the 1980s to forecast officer retention rates in the Army and Air Force. While the RAND Corp. DRM yielded a myriad of useful predictions, limited computing power at the time of the model's creation necessitated extreme parsimony in the model.
- We recommended exploiting the many advances in econometric techniques, better data, and exponentially increased modern computing power (by using high performance computing cluster servers) to build new DRMs from the ground-up. Such a model could be used alongside other previously used models to provide additional insights and predictive power.

In this second report, we proceed along two lines:

First, we collect a rich administrative dataset of Navy officers and examine their career trajectory, paying particular attention to their educational background and sociodemographic characteristics.

Using long-term trend, as well as regression analysis, we find the following:

- Significant retention rate differences arise, especially over the long run, across gender, marital and dependent status, race, and education level.
- Married males with graduate degrees who have children, on average, have the longest career with the Navy.
- Somewhat surprisingly, officers with a science, technology, engineering, and math (STEM) background seem to be no more likely to separate from the Navy compared to those without a STEM background.

- For gender, race, and marital and dependent status, differences in retention rates widen sharply relatively early in the officers' careers (until approximately year of service 5) and stabilize from then onward.
- For graduate degree status, the gap in retention rates opens up quickly and continues to widen through 20+ years.
- While the long run trends and regression results are illuminating, we should be wary of drawing definite conclusions about innate ability or desire of officers to stay or separate based on these analyses. If leadership identifies good officer candidates for further advancement and subsidizes graduate education, officers with graduate degrees should be expected to enjoy a longer career in the Navy due to rapid/on-time promotion.
- We do not yet differentiate whether separation was voluntary or forced.
- The observed trends could be impacted by Department of Defense policy, cultural influences, or outside economic forces that may act differently on each sub-group analyzed
- Without a formal model to distinguish between correlation and causation, the findings in this study simply help to direct our modeling efforts in subsequent years.

Second, we provide an in-depth description of dynamic programming models: We start with a general description of dynamic programming, demonstrating the usefulness and internal consistency of the model in being able to predict rational, forward-looking agents making choices that affect their future. We then describe some of the technical difficulties of computing such a model and survey recent advances in the literature that may help to alleviate these problems.

Next, we provide a more detailed technical description of the model, defining value functions, Bellman's equations, and other concepts necessary to program, estimate, solve, and simulate a dynamic programming model.

Recommendations for Further Research

Synthesizing these two lines of examination, we propose a path forward, which includes: collecting additional data on officers, and program the dynamic programming model considering the unique labor market circumstances of naval officers; accounting for monetary and non-monetary compensation policies that may affect individual decisions to remain or separate from the Navy; "condition" on the observable quality characteristics of the officers (such as education level, major of study, Fitness Report scores, etc.) to assess whether the Navy is losing its best and brightest; incorporating the state of the economy, such that officers are not making career-altering decisions in a vacuum; and performing these analyses for separate Military Occupational Specialties to examine how officers in different communities may make different career choices.

NPS-19-N039-A: Cyber System Assurance through Improved Network Anomaly Modeling and Detection

Researchers: CDR Chad Bollmann USN Ph.D.

Student Participation: Mr. Jorge Gonzalez CIV INT and Mr. Joshua Clymer CIV INT

Project Summary

The aggregation of computer network traffic in the network core will cause certain features of network traffic, including packet rate, to follow either Gaussian or alpha-stable distributions. The resulting distribution is determined by the nature of the individual traffic inputs. A diverse device population will typically result in alpha-stable traffic, while a homogeneous device population will usually produce Gaussian-distributed aggregate traffic. When traffic aggregates to alpha-stable distributions, network anomaly detection algorithms designed using alpha-stable assumptions will perform better than algorithms based on Gaussian assumptions.

Keywords: *alpha-stable, network anomaly detection, renewal theory, generalized central limit theorem, GCLT*

Background

It is accepted that some aspects of aggregated network traffic (e.g., inter-arrival times, packet and byte volumes per unit time) can be more accurately characterized using heavy-tailed models (Bollmann, Tummala, McEachen, Scrofani, & Kragh, 2018, p. 5524; Paxson & Floyd, 1995, p. 226; Simmross-Wattenberg et al., 2011, p. 494). This acceptance is complicated by observations that in smaller networks or under certain traffic conditions, the same features instead appear to possess exponential-tails (i.e., become Gaussian). However, little theoretical explanation exists for the co-existence of alpha-stable- and Gaussian-distributed traffic.

If aspects of network traffic are heavy-tailed, non-parametric (i.e., distribution-agnostic) test statistics as well as parametric test statistics (which require the presumption of a specific distribution) developed for heavy-tailed inputs, should demonstrate superior performance when compared to inappropriate parametric tests such as mean and variance. The principle investigator (PI) has previously shown that non-parametric, alpha-stable test statistics outperform Gaussian tests (Bollmann, 2018), but combinations of parametric test statistics have not been evaluated.

Findings and Conclusions

This study began with a literature review of network anomaly detection work grounded in heavy-tailed processes; no significant published works were found since the PI's dissertation literature review. An additional literature review into the history of alpha-stable network traffic theory was completed, and a series of works linking self-similarity, long-range dependence, heavy-tailed traffic characteristics, and alpha-stable distribution theory were identified.

From the assumption that network communications from an individual device can be treated as independent, identically-distributed (IID) random processes, two proven literature models support the aggregation of these IID processes to an alpha-stable result. The first, impulsive-based model, via the

Generalized Central Limit Theorem (GCLT), demonstrates that IID processes of infinite variance will produce an alpha-stable result. When the individual IID processes exhibit finite variance, which can occur when devices and processes are relatively similar, a Gaussian aggregation results. The second aggregation model, based on renewal theory (Taqqu & Levy, 1986, p.73) that individual traffic impulses possessing varying “on” and “off” times can similarly aggregate to alpha-stable or Gaussian processes.

Two simple modeling algorithms were developed to validate the aggregation theories. First, individual device impulses (i.e., inputs) were cataloged from five seconds of four different network traffic traces based on source and destination internet protocol addresses and port numbers. These impulse catalogs were then used to reproduce (i.e., model) the source traffic and compared to the original traffic distributions using cumulative distribution function (CDF) plots and Kolmogorov-Smirnov (KS) test values as similarity measures. The KS test values indicate that the renewal model is slightly more accurate than the impulse model, but both models satisfactorily predict the original distribution. This conclusion is particularly promising because time constraints prevented significant refinement of the models.

The theoretical support of the impulse and renewal models for either Gaussian or alpha-stable distributions validates our hypothesis that alpha-stable models more accurately describe network traffic. Because the Gaussian is a special case of the alpha-stable distribution (where the tail parameter = 2), the alpha-stable distribution becomes the only logical choice for network traffic models and, by implication, anomaly detection test statistics.

Testing parametric, alpha-stable derived anomaly detection statistics was the focus of the second portion of our work. The parametric test results validate our hypothesis that alpha-stable test statistics outperform Gaussian tests, and that parametric tests slightly outperform non-parametric tests. One important finding is that the alpha-stable accuracy improvement margin is greater at lower false alarm rates; for any statistical implementation to be commercially viable, detection thresholds must be set such that false alarm rates less than one percent.

The period of performance for this project concluded before additional traces could be evaluated and all intended detector implementations could be evaluated. An eventual goal of this work is to use the labeled data and alpha-stable fits as input to a machine learning detection approach; preliminary qualitative evaluation has shown that the results would be well-suited to a clustering approach due to easily-identifiable separation boundaries between benign and attack traffic cases.

As previously discussed, the overall results from this study integrate nicely with the existing body of work describing Internet traffic as self-similar and long-range dependent with scaling properties; these characteristics all relate to or result from alpha-stable network traffic. The characterization of traffic inputs as impulsive provides an intuitive method of using established renewal theory to show that aggregated traffic should approach Gaussian or alpha-stable limits. Additionally, this study is the first to propose an explanatory method of predicting aggregated traffic distributions and characteristics that have long been determined only empirically. The long-term implications of this study are that the accuracy of network traffic measurement and analysis may be significantly improved through utilization of existing alpha-stable-based approaches, as well as development and application of novel alpha-stable methods, particularly with respect to machine learning. Note: the data used in this work is evaluated as highly reliable and reflective of real-world network traffic.

Recommendations for Further Research

Several areas of this research topic warrant additional exploration. First, both the impulse and renewal process models should be assessed both qualitatively and quantitatively against network traffic traces consisting of different numbers and types of devices. The extensibility of this model to wireless network traffic also bears investigation, as different protocols facilitating the multiple access environment will alter the ON-OFF times of device transmissions. Examination of the quantitative results would permit selecting either the impulse or renewal model as the frequently “best” alternative for future research and development. Once validated, fingerprinting methods should be evaluated for the renewal process model with a goal of identifying optimum quantities of stored network trace data. Development of a fingerprinting method could permit saving high-quality, reduced-volume samples (i.e., snapshots) of network traffic sources and aggregated traffic that could serve to inform long-term models and anomaly detection systems.

Next, the ensemble anomaly detection systems, consisting of combinations of both parametric and non-parametric alpha-stable test statistics can be developed, evaluated, and optimized. These systems could integrate Gaussian test statistics in order to reduce computational overhead and detection delays when the traffic modeling and evaluation system senses Gaussian traffic characteristics. Finally, the ability of the detection system to rapidly detect anomalies should be rigorously examined; the resistance of the alpha-stable methodology to outlier skew implies that anomalies could be reliably identified using a minimum of subsequent samples. These minimum-repeatability tests would significantly improve overall detection system performance and system response times to denial-of-service attacks, improving network resiliency.

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NPS-19-N091-A: Modeling Large-Scale Warfighter Cognitive Reasoning and Decision-Making Using Machine Learning, Artificial Intelligence and Game Theory (Continuation)

Researcher: Dr. Ying Zhao

Student Participation: No students participated in this research project.

Project Summary

In this research, we developed a process for leveraging artificial intelligence (AI) to learn, optimize, and win a general asymmetrical war game; no previous researchers have been able to successfully apply machine learning (ML)/AI/game theory (GT) methods in this way. We confirmed that when modeling large-scale warfighter cognitive functions such as reasoning and decision-making, we need to combine technologies in ML, AI, and GT to best help warfighters, learn from them, and reduce their cognitive burden. We also showed using a simulation data set that leverage AI to learn, optimize, and win (LAILOW) is essential to improve the performance of mission planning capabilities for an AI assistant because it allows holistic learning, automation, and optimization of the whole kill chain or kill web operations in a war game environment, whereas traditional methods can only study small portions of the process. The white paper for this research has been accepted as a poster in the AAAI 2019 fall symposium (Zhao & Nagy, 2019).

War game communities, such as commanders in the Naval War College (NWC) and mission planners in the air wings of a carrier, could benefit from our research. The sequential asymmetrical war game design can be also extended to other areas of defense applications, including C-C4ISR, assured command and control (C2), and modeling and simulation to achieve decision-making superiority and improve readiness.

We first developed a generic representation of a multi-segment sequential war game with two opposing asymmetrical players. For one player—the self-player of a blue force—actions are placed into categories that represent actions or tactics in five typical warfare domains or cross-domains familiar to military strategists and mission planners: Intelligence, surveillance, and reconnaissance (ISR); C2; mission planning (MP); platforms; and information operations (IO). Probabilistic rules—“events to actions” and “actions to events”—define the valid actions for each player. The two opposing asymmetrical players have their own sets of rules guiding their corresponding valid actions; valid actions can be defined by subject-matter experts (top-down) or data-mined from war game logs and data from doctrines and from the mission planning communities (bottom-up). Events generated by the players’ actions happen sequentially in each segment. We then developed game-theoretic frameworks and tested tools for a player to LAILOW the game, and then we applied LAILOW to a real war game in the context of over-the-horizon targeting.

Keywords: *machine learning, ML, artificial intelligence, AI, game theory, GT, war game, mission planning, MP*

Background

Tremendous advancement in commercial applications of big data and deep analytics have recently occurred, including ML and AI methods; these technologies have the potential to address the unique

challenges of modeling complex functions of warfighters, including reasoning and decision-making. In our previous work, we studied the theory and practice of Soar, which is a cognitive architecture (Laird, 2012), and RL (Sutton, 2014), and a class of ML/AI algorithms shown to be capable of automating some cognitive functions of warfighters, such as the decision-making of a tactical action officer in a CID task (Zhao, 2016; Mooren, 2017; Zhao et al., 2017, 2018).

The objective of this project was to study the potential to apply Soar and other ML/AI/GT techniques to new areas of military applications, including C-C4ISR, assured C2, modeling and simulation, war games, and MP, to achieve decision-making superiority and improve readiness in the vast, complex, and uncertain domains of cybersecurity and information warfare.

Findings and Conclusions

We modified the Soar-RL algorithm in important ways for the war game: first, we modified it so it can be used inside the loop of the game frameworks, and be combined with a genetic coevolution AI algorithm, next, we modified Soar-RL in the form of online learning and adaptation toward a trusted AI. When cognitive functions of warfighters are to be automated by an AI assistant, one needs to implement an AI assistant to gradually learn from a human master and so improve—not only to achieve better machine learning, but also to allow it to gain the trust of humans through an interactive process. We thereby showed that machine learning techniques, such as online learning and adaptation of Soar-RL, can be used as a tool to bridge the “trust” between human and machine (Zhao et al., 2018).

We then applied LAILOW to a real war game in the context of over-the-horizon targeting. We showed that, because LAILOW is used under a game framework, it needs to constantly look at the self-player in a war game environment, and suggests winning actions based on the nature of an opponent as follows (Zhao & Nagy, 2019):

- Case 1: opponent performs random actions (e.g., weather or other uncertain environmental factors)
- Case 2 (strategic complement game): opponent’s actions show interest in the actions taken by the self-player (e.g., allies respond to self-player’s actions).
- Case 3 (strategic competition game): opponent takes deliberately adversarial actions minimizing the effect of the self-player’s actions (e.g., a cyber attacker’s opponent counters an attack).

By applying the combined frameworks and techniques to our sequential war game with asymmetrical players, we demonstrated an advancement in state-of-the-art of ML/AI/GT theory and practice.

Recommendations for Further Research

Two recommendations for future research are as follows: continue the research on, development of, and investment in modeling large-scale (with both big data and no data), trusted, adaptive, and causality-conscious warfighter cognitive functions using ML, AI, and GT algorithms or the LAILOW system, and improve the technology readiness level towards achieving module and/or subsystem validation in a relevant environment and module and/or subsystem validation in a relevant end-to-end environment (Blanchette, Albert, & Garcia-Miller, 2010).

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NPS-19-N143-A: Aviation Depot Maintenance Throughput Optimization

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Student Participation: Maj Kyle Ellis USMC

Project Summary

Aviation readiness including, but not limited to, the Super Hornet cannot be described as simply a maintenance problem or a funding problem. It is a systems problem and must be addressed with a system dynamics approach. Unfortunately, the performance/pricing models (P/PMs) studied in this research represent only a very limited piece of the system. Much human decision-making goes into the process, for example, planners make funding decisions based on multiple factors including changing operational environments, budgetary constraints, and leadership priorities. Therefore, a systems dynamics approach is needed not only to model the interactions between P/PMs, but also to remove as much of the human element as possible, as basic skills do not give those individuals involved a full understanding of the intricacies of a singular model, much less the relationships between related models.

Keywords: *F/A-18, Super Hornet, aviation, readiness, performance/pricing model, P/PM, Chief of Naval Operations*

Background

The Department of Defense (DoD) is nearly seven times larger than the next largest government agency in terms of annual budget request (Headquarters USAF, 2016). The DoD therefore requires a more in-depth budgeting process than the single-year outlooks of smaller departments. Since 1960, the planning, programming, budgeting, and execution (PPBE) process has been the DoD's primary method of allocating resources and is guided by the Quadrennial Defense Review, force development guidance, program guidance, and budget guidance (DoD Directive 7045.14, 2013).

The long-term prediction of allocations necessitates a systematic approach to requirement analysis. In the Navy, this responsibility falls largely on the Deputy Chief of Naval Operations for Integration of Capabilities and Resources, who "exercises centralized supervision and coordination for the Navy's capability study analysis and assessments, allocation and integration of the Navy's resources and requirements in the PPBE, and determination of technical guidance" (Chief of Naval Operations [CNO], 2018). Subordinate to N8, N81 is responsible for the assessment of Navy's warfighting capability including evaluating the Navy's ability to counter current and future threats, the Program Objective Memorandum (POM) in the areas of manpower, fleet readiness, and logistics capability delivery (wholeness), and other areas of importance to the CNO such as tactical aviation readiness.

Part of N81's assessment of the POM is the accreditation of models used during the budgeting phase by Navy resource sponsors of programs with operating appropriations of \$50 million or more (CNO, 2006). These models are analytical tools used to relate budgeted costs to observed performance levels. However, during recent POM development cycles, performance levels have not met forecasted performance for many programs and N81 has been tasked with identifying the potential causes. N81 is attempting to determine if current level-of-effort thresholds are sufficient to accurately determine the appropriate level of accreditation, the cause of variance between P/PM-informed budget projections and subsequent execution, the accuracy of external P/PM inputs, and internal P/PM algorithms and cost estimation relationships. This thesis supports the efforts of N81 and focuses on the subset of models that are directly tied to tactical aviation, particularly the F/A-18 Super Hornet.

Findings and Conclusions

This research consists of a qualitative analysis of all inputs and outputs of four aviation-related P/PMs. It also utilizes quantitative methods such as regression analysis to attempt to link Super Hornet readiness rate to varying input or output parameters. This provides N81 a robust framework to build a conceptually integrated model of the interdependencies of these four P/PMs. Our research is exploratory in nature and intended to be a foundation of future work. As such, most of the research questions remain unanswered. Aviation readiness including, but not limited to, the Super Hornet cannot be described as simply a maintenance problem or a funding problem. It is a systems problem and must be addressed with a system dynamics approach. Unfortunately, the P/PMs studied in this research represent only a very limited piece of the system. Regardless of how well each individual model works in its own subsystem, the overall system cannot be adequately understood without modeling it in its entirety. This is not a novel conclusion; in fact, this realization was the basis for N81 to commission this work.

The human element is prevalent throughout the system. It is evident beginning with the annual data calls in which stakeholders extract, format, and submit the execution and costing data used in the Flying Hours Program (FHP) to the Aviation Engine Depot Readiness Assessment Model (EDRAM) model manager using his "significant subject matter expertise regarding the realities of Navy aircraft repair as it is actually

performed” to adjust the model inputs and constraints (Pandolfini & Phipps, 2015, p. 6). Furthermore, due to the planning, programming, budgeting, and execution (PPBE) process, planners make funding decisions based on multiple factors including changing operational environments, budgetary constraints, and leadership priorities. A systems dynamics approach is needed not only to model the interactions between P/PMs, but also to remove as much of the human element as possible.

Active duty positions with direct interaction with or oversight of the P/PMs are filled with mid-level officers who generally change positions every two to three years. By this point in their careers, these officers are adept at learning skills needed for new positions and can achieve a basic level of proficiency relatively quickly. Rules of thumb, standard operating procedures, and standardized languages all help the officers to transition, but basic skills do not give them a full understanding of the intricacies of a singular model, much less the relationships between related models. Instead, this requires tacit knowledge, described by Nissen as knowledge which is “gained principally through experience and accumulated over time, organizational capabilities based upon tacit knowledge are difficult to imitate” (2006). P/PM model managers have extensive understanding of the feasibility of input data for the model, but relying so heavily on a model manager who eventually will vacate the position poses risks.

These risks are multiplied by what Theorgood called a “dearth of proper documentation of modeling and simulations (M&S) development efforts, (validation, verification, and accreditation) procedures, and most notable the configuration management plan” (2005). Indeed, documentation obtained for this study was often incomplete. For example, P/PMs are required to be re-accredited every three years; however, a partial 2011 verification and validation (V&V) submission and the full 2015 accreditation report was the only documentation available for this study.

The Navy can mitigate risk in two ways: first, modifications to the P/PMs algorithms and business rules can reduce the reliance on managers and the knowledge they possess. In the EDRAM example above, the manager’s extensive knowledge of the feasibility of input data should be captured as constraints, thereby reducing the reliance on hard-to-reproduce tacit knowledge. Second, as suggested by Theorgood, a robust system for depositing and retaining M&S documentation should be developed. All development documentation, V&V submissions, accreditation reports, input data, and model projections should be retained and made readily assessable not only to the model owners and managers, but also to analytical activities at N81.

Recommendations for Further Research

The next logical step for follow-on research is to conduct an in-depth, quantitative analysis to validate the assumptions and conclusions of this work, while also addressing its shortcomings. Researchers should focus on the entire decision supply chain, that is, from the depot to the flight line, in order to gain a sense of how the readiness goals that govern the depots represent actual utilization in the fleet. Special attention should also be given to integrating the DRAM suite and the FHP.

This research has mapped the logical connections between three of the four models examined, but further work is needed to fully describe these interactions. This will not be a purely quantitative analysis, as there is still qualitative research needed to conceptualize exactly how the models interact. For example, the FHP produces a flight hour requirement in the OP-20 format. Those hours are used to generate the budgeted flight hours and the flight line entitlement, which become key drivers to the EDRAM and Aviation Airframe Depot Readiness Assessment Model (ADRAM), respectively. However, there is not a direct path

from the FHP to these inputs. In fact, the OP-20 report passes through several iterations which include deletions and other adjustments; the same is true for the DRAM inputs. This process comprises both automated and manual adjustments whose logic and human-based rules need to be specified in as much detail as possible before any quantitative assessment can begin.

Similar investigation of the sparing models is also required. As mentioned above, the lack of model documentation severely hampered efforts to include these models in this work, but this does not diminish the importance of spare inventory to mission capable (MC) rates. The coming integration of the Naval Aviation Readiness-Based Sparing model and the fact that it was developed at the Naval Postgraduate School at the behest of the Naval Supply Systems Command means that technical documentation is readily available, as opposed to that from some of the legacy, proprietary models.

Once all four models and their interactions are sufficiently understood, the research can expand beyond the F/A-18 Super Hornet. Each type/model/series in the naval aviation inventory represents unique challenges in terms of maintaining MC aircraft. However, similar to the way the P/PMs inform funding decisions for all naval aircraft, the supply and maintenance pipelines are shared in part, if not wholly, across the enterprise. Therefore, the relationships described in this research, as well as those uncovered in follow-on work, will be translatable across the fleet. The techniques used may also lend themselves toward the evaluation of funding decision models used for the surface and subsurface Navy.

Finally, in September 2018, the Boston Consulting Group began a four-week assessment of Fleet Readiness Center Southwest operations. The Navy should consider a similar consulting arrangement to provide insight regarding PPBE activities for aviation.

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NPS-19-N257-A: In-stride Optimal Motion Planning/re-planning for MCM Missions using Optimization

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Student Participation: LT Bryan Lowry USN, LT Joshua Sale USN, LT Christopher Price USN, LT Richard McClain USN, and LT Justin Laddusaw USN

Project Summary

Unmanned vehicles have become increasingly important for naval mine countermeasures (MCM), but they have not yet realized their full potential to reduce mine clearance timelines while providing sufficient risk level guarantees. Mine hunting operations typically employ multiple search, identification/classification, and neutralization sorties. These tasks are often conducted as sequential phases, each employing different vehicles and sonar sensors. This approach requires laborious post-mission analysis and planning cycles between each phase. Our research seeks to overcome the limitations of this sequential search paradigm by enabling simultaneous deployment of dissimilar vehicles with complementary capabilities.

Specifically, we investigated new algorithms and computational tools for generating optimal search trajectories for heterogeneous, multi-vehicle teams in a real-time, event-based framework. Simulations verified that these new techniques are orders of magnitude faster than previous algorithms, yet still achieve equivalent search performance. Significantly, these techniques do not require specialized computing equipment. Therefore, these algorithms are suitable for implementation on unmanned vehicle autopilots, a key capability for in-stride optimal mission planning and re-planning by collaborative vehicle teams. The ability to conduct simultaneous mine hunting sorties with multiple autonomous vehicles promises to improve the speed and effectiveness of MCM missions.

Keywords: *optimal search, mine countermeasures, MCM, mine hunting, sonar, mission planning, autonomous vehicles, UUVs*

Background

Mine countermeasures (MCM) is an extremely challenging and complex Navy mission set. A number of different capabilities and techniques are required to confront the wide variety of potential threats and operational environments encountered (U.S. Navy, 2004). Unmanned vehicles and advanced sensor systems now play an integral role in these operations, so it is imperative that MCM commanders and vehicle operators have the ability to maximize the efficiency and utility of these resources.

The objective of this research is to develop in-stride MCM planning algorithms that allow a team of heterogeneous vehicles to conduct mine detection and identification/classification missions in tandem instead of sequentially. Recent theoretical work by Phelps, Gong, Royset, Walton, and Kaminer (2014)

produced a mathematical and computational framework called Generalized Optimal Control (GenOC). Leveraging a numerical toolbox developed by Walton (2015), GenOC has been used to solve optimal search problems with realistic mine hunting vehicle and sonar models (Kragelund, 2017; Kragelund, Walton, Kaminer, & Dobrokhodov, 2018). Although GenOC trajectories outperformed conventional area coverage patterns under the same time or resource constraints, initial trajectory optimization routines were so computationally expensive that solutions had to be computed off-line, which precluded in-stride planning.

To achieve a true in-stride planning capability for MCM, motion planning algorithms must 1) update target distributions, 2) address false targets, and 3) re-compute new search trajectories in near real-time. The first two issues have been analyzed by Walton, Kragelund, and Kaminer (2017), and additional methods for dealing with false targets were reviewed during this study. The majority of our research effort, therefore, investigated computationally efficient planning algorithms based on Bezier curves to achieve near real-time optimal motion planning (Cichella, Kaminer, Walton, & Hovakimyan, 2018).

Findings and Conclusions

The Naval Surface and Mine Warfighting Development Center supports research and development needed to better understand and optimize the sensor and vehicle performance of next-generation MCM systems. The results of this study support the topic sponsor's ultimate goal of providing a faster and more effective search, identification/classification, and neutralization timeline for the MCM commander. The ability to conduct these missions simultaneously with multiple autonomous vehicles has great potential for future MCM operations.

In general, the presence of false targets in the search area requires a two-stage search strategy: 1) broad search to detect contacts, and 2) contact investigation to distinguish actual targets from false targets. Therefore, our study examined different ways for cooperating vehicles to plan contact investigation trajectories on demand. The literature describes several methods for dealing with false targets during a search operation. Many utilize a Poisson probability distribution to model the number, location, and detection of false targets (Stone, 1989; Kalbaugh, 1992; Decker, Jacques, & Pachter, 2007). We conclude, therefore, that the GenOC model-based solution framework can accommodate false-target searches with slight modifications to the objective function being minimized. Other potential objective functions include the risk due to undetected mines after MCM (Washburn, 2006; Monach & Baker, 2006), or the risk of incorrectly estimating the number of targets present in an area (McMahon, Yetkin, Wolek, Waters, & Stilwell, 2017).

Our research also examined the computational barriers to in-stride planning posed by initial GenOC implementations. Significant complexity stems from the methods used to approximate vehicle trajectories and discretize the search problem for numerical solution (Phelps et al., 2014). Since vehicle dynamics place constraints on vehicle state and control trajectories that must be satisfied at discrete times, solutions are also sensitive to the number of time nodes chosen (Kragelund, 2017). This study analyzed GenOC performance improvements achieved by modifying the problem formulation in three ways. Specifically, we adopted the methods described by Cichella et al. (2018) to 1) exploit the differential flatness of search vehicle dynamics and 2) approximate vehicle trajectories with Bernstein polynomials. These two improvements reduced the number of constraints on the optimization, and produced smooth numerically-stable Bézier curves as output trajectories, respectively.

The degree elevation property of Bézier curves (Cichella et al.,2018) enabled our third modification, a continuation algorithm based on homotopy methods similar to one described by Dobrokhodov, Walton, Kaminer, & Jones (2020). This approach iteratively solves a sequence of simple problems to arrive at an optimal solution in fewer iterations; beginning with a trivial problem, each solution supplies the initial guess for the next problem.

Our continuation algorithm first computes the best low-order Bézier curve trajectory, then uses degree elevation to successively find higher-order Bézier curve trajectories from lower-order initial guesses. These modifications drastically improved solution times. A desktop computer running standard optimization software can now solve MCM search problems about 50 times faster than prior GenOC implementations using specialized software on the NPS Hamming supercomputing cluster (Kragelund, 2017). We conclude, therefore, that these algorithms are suitable for implementation on unmanned vehicle autopilots, a key capability for in-stride optimal mission planning by collaborative vehicle teams.

Recommendations for Further Research

McCray describes a promising approach for planning optimal, semi-adaptive searches that uses interim search results to update probability densities for both real and false targets, based upon prior intelligence about their relative spatial distribution (2017). Future research should investigate whether this technique can be applied to learn the parameters of a minefield's laydown pattern to inform future search plans. In addition, since GenOC offers a centralized method for planning MCM missions, we recommend that future research investigate distributed, event-driven planning and information sharing methods.

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N9 - WARFARE SYSTEMS

NPS-19-N106-A: Robust Modeling & Simulation to Support Medium Displacement Unmanned Surface Vehicle (MDUSV) Mission Set Development

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Project Summary

As the U.S. Navy continues the development of Medium Displacement Unmanned Surface Vehicles (MDUSV), a doctrinal shift of the surface fleet necessitates examining potential manned-unmanned teaming mission sets within the construct of Distributed Maritime Operations (DMO). Utilizing systems engineering for architectural development, discrete-event simulation, and analysis, this study evaluates MDUSV performance of an intelligence, surveillance, reconnaissance, and targeting mission in support of a two to three ship Adaptive Force Package's (AFP) over-the-horizon surface strike. The results indicate a large benefit associated with utilizing passive sensors on MDUSVs in lieu of an active radar, and that the magnitude of this benefit increases when lofting the passive sensors on towed airborne arrays. In this study, extensions to MDUSV communications and operating ranges, in some configurations, led to detections of the enemy further from friendly manned vessels, but decreased the survivability and lethality of the main body, when these ranges eclipsed the lowest ranged surface-strike weapons in the inventory. Additionally, while overall effectiveness increased with an offensive jammer on MDUSV, defensive countermeasures provided no discernable improvement to the AFP's performance. One recommendation from our study is to focus future related research on allowing for Emissions Control (EMCON) policy execution and manned-unmanned teaming.

Keywords: *unmanned systems, unmanned surface vessels, Medium Displacement Unmanned Surface Vehicles, MDUSV, Distributed Maritime Operations, DMO, operational analysis*

Background

This research demonstrates that the MDUSV can contribute to a 2016 concept documented in Surface Forces Strategy (Rowden, 2016). In this article, Vice Admiral Thomas Rowden introduced the concept of Distributed Lethality (DL): the U.S. could better establish sea control where and when required through the combination of “increasing the offensive and defensive capability of individual warships” and operating these warships in geographically displaced AFPs. The Navy later grew the concepts of DL into the total system approach of DMO. In 2018, the Chief of Naval Operations, Admiral Richardson, designated DMO maturation as a primary focus area to strengthen “naval power at and from the sea” (Richardson 2018).

Our research examined how MDUSV could be employed to increase AFP mission success in a DMO environment. A revised problem statement directed research into MDUSVs supporting AFPs in an over-the-horizon targeting (OTH-T) surface-to-surface strike. Within this potential mission area, four project objectives were explored. These included researching communications methods required to support OTH-T operations of MDUSV, evaluating the benefits of different sensor types for detection and targeting, examining MDUSV electronic attack capabilities, and understanding the relationship between MDUSV defensive countermeasures and AFP effectiveness. One of our primary hypotheses was that communication ranges enabled through a MQ-8 relay allow the MDUSV to push further ahead of the AFP, and enable the AFP to strike from greater distances.

Findings and Conclusions

Outside of seaworthiness and logistical concerns, operational analysis yielded three top-level activities: Communicate with the AFP, Perform Intelligence, Surveillance, Reconnaissance (ISR), and Support Engagement. In support of Communicate with the AFP, a scenario pre-condition of unavailable satellite communications (SATCOM) was imposed requiring the MDUSV to station within line-of-sight ranges to communicate with the AFP. Perform ISR refers to the detection, correlation, and tracking of threats. Support Engagement includes the activities of providing fire control information to the AFP and performing an electronic attack (EA).

Operational and functional analysis resulted in the following allocation to a MDUSV capable AFP. Communication functionality refers to the exchange of sensor and control information. Varied for simulation, this functionality maps to mast-height antenna data exchanges, an antenna directly connected to the MDUSVs but elevated by a Towed Airborne Lift of Naval Systems (TALONS), or an airborne relay from AFP-launched rotorcraft. Sense functionality (find, fix, and track) includes either passive sensing functionality (physically mapping to sensors such as electronic support measures [ESM]) or active sensing functionality (mapping to surface-search radar). Passive sensor functionality also leverages TALONS. C2 Functions includes AFP battle management and engagement control functionality. EA is included here as an offensive spectrum jammer on MDUSV. Last, Self-Defense refers to various countermeasure functionality implemented on the AFP and MDUSV. Of note, no conventional weapon functionality was included with the MDUSV.

A discrete event simulation was developed using the program ExtendSim. Inputs including communications range/antenna height, sensor mode, offensive jamming, and MDUSV countermeasures were varied across runs. Additionally, the number of MDUSVs available to the AFP ranged from 0-10. Three configurations of AFP manned vessels were used: one DDG-51 Flight III and two Littoral Combat Ships (LCS), two DDG-51 Flight III and one LCS, and two DDG-51 Flight III without LCS. In addition to

publicly available defensive capabilities of the vessels, an assortment of future surface-strike weaponry was assigned to each vessel. The Red force was defined as a very capable, mixed package of ships, weaponry and sensors. Simulation outputs corresponded to measures associated with the functions, operational activities, and project objectives.

The measures of effectiveness (MOE) covered the entire engagement sequence and included First-to-Fire, Destroyed Enemy Forces, and Number of Manned AFP Assets Destroyed.

Our hypothesis that communication ranges enabled through a MQ-8 relay allow the MDUSV to push further ahead of the AFP and enable the AFP to strike from greater distances was determined to be incorrect when using surface-search radars, as Red frequently detected and destroyed the MDUSV before Blue achieved a first detection. However, when the MDUSV employed ESM the MDUSV enabled Blue to achieve a detection and fire before Red. Despite this, extended communication ranges did not largely impact the First-to-Fire MOE and resulted in higher AFP manned vessel attrition and lower Red losses. These counter-hypothesis results are primarily linked to the AFP vessel and weapon configuration. While extended communications range functionality may still be desirable for MDUSV and AFP, designs and doctrine should balance the benefits of early knowledge with the cost of exceeding the ranges of even a portion of the AFP surface-strike weapon inventory.

The results for sensor mode variation indicated that operating an underpowered radar on the MDUSV led to early MDUSV attrition, whereas the ESM system generally allowed Blue to receive an MDUSV generated track before Red detected Blue. This slight advantage drastically improved when ESM ranges were extended by elevating the system on TALONS. Even without TALONS, passive ESM was a very significant benefit across all MOEs; forgoing active radar for ESM led to improved AFP effectiveness. Following this, while a feasible MDUSV radar may add value in other missions, the use of it in a high-threat environment should be curtailed. Future MDUSVs should include robust ESM systems. They reduce the susceptibility of the MDUSV and greatly improve AFP effectiveness. While more feasibility research is needed, the greatest benefits were realized when the sensor was elevated via TALONS.

Recommendations for Further Research

This research builds upon previously examined MDUSV and DMO topics and contributes valuable simulation data to inform/guide potential decision-makers. Future work areas that were identified as pivotal to the overall evaluation of MDUSV employment yet were not captured in detail through the research include: allowing for EMCON policy execution and manned-unmanned teaming, utilizing SATCOM, comprehensive battle management and fire control logic, modeling more detailed sensor quality, and portraying more diverse engagement geometries.

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NPS-19-N110-A: Modeling and Analysis of Total Ownership Cost for Surface Ship EO/IR Systems

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Student Participation: LT Eliah Ledbetter USN and LT Katelyn George USN

Project Summary

In this research, we look at answering the following: Would an advanced analytical model be a more effective metric to estimate total ownership cost (TOC) with life-cycle cost under uncertainty and risk than the current method of life-cycle cost estimates for Surface Electro-Optical Infrared Sensors (EO/IRs)? To accomplish this, the research developed and analyzed a computational model for TOC with Life-Cycle Cost Model Under Uncertainty for EO/IR. During the development of the model, we identified the required data and examined the current Department of Defense (DoD) method for determining system life-cycle costs for defense systems, and determined that the proposed model is a useful alternative to the current method of determining the life-cycle costs for EO/IR on surface ships. Finally, we concluded that the developed model can be applied to cost estimating in other sectors of DoD cost projections.

Keywords: *total ownership cost, simulation, risk analysis, ROI, return on investment, cost modeling, cost estimation*

Background

The purpose of this research was to develop a model to estimate total ownership with life-cycle costs under uncertainty associated with EO/IR. We will examine the basics of Total Ownership Cost modeling over the life cycle of the EO/IR s, including the inception phase of Acquisition Costs, followed by annual Operations and Maintenance (O&M) expenses, along with a final set of Disposition Costs at the end of life of the sensor. This model will allow managers to have better decision analytics of the costs of the sensors for use in subsequent cost comparisons across sensor platforms, return on investment analysis, portfolio allocation of resources, and analysis of alternatives.

Findings and Conclusions

The final deliverables of the research included a detailed report, computational Excel model with risk-based simulation assumptions and forecasts, a training video, and research poster. These deliverables were meant to get the user of the model started with applying the basics of TOC modeling over the life cycle of the EO/IR, including the inception phase of acquisition costs, followed by annual O&M expenses, and a final set of disposition costs at the end of life of the sensor. This research was not meant as guidance on design specifications, but, rather, as a guide to the decision analytics modeling of the costs of the sensors for the purposes of use in subsequent cost comparisons across sensor platforms, return on investment analysis, portfolio allocation of resources, and analysis of alternatives. The methodology and model will allow decision makers to have better decision analytics of the costs of the sensors for use in subsequent cost comparisons across sensor platforms, return on investment analysis, portfolio allocation of resources, and analysis of alternatives.

The accurate calculations of these costs were not as straightforward as their descriptions imply. To accurately incorporate cost factors, it was essential to consider economic theory; the elements of time valuation of money were critical in the analysis of alternatives. Therefore, economic growth, the annual discount rate, inflation, and opportunity cost of investing in a specific system were essential to our study. Other factors include budgetary cutbacks and changes in technology. The model will allow the user to input these changes to manually adjust for each of these. Utilizing this model will serve as a proof of concept to understand how this approach could be used to reduce cost overflow and prevent budget overruns. It will provide greater insight into the true nature of the cost of cash outflow and the life cycle of the product and its associated costs. These results would give leaders a more effective metric to analyze total ownership cost under uncertainty, therefore allowing leadership to make more informed decisions in the DoD acquisition process.

Recommendations for Further Research

There are several goals that may be pursued as future work on this project: first, additional data may be collected and run through the prescribed model and methodology, as the current research only utilized nominal and rough order magnitude estimations; secondly, multiple systems can be run through the same methodology to test its robustness as well as ability to handle cross-platform technologies; finally, analysis of alternatives can be added to the existing methodology to enhance its applicability throughout the DoD.

NPS-19-N112-A: Manned-Unmanned Teaming in Distributed Maritime Operations

Researchers: Dr. Mark Nissen and Dr. Shelley Gallup

Student Participation: No students participated in this research project.

Project Summary

As a key tenet of distributed maritime operations (DMO), available manned and unmanned, surface and air, combatants and sensors require integration to serve as a cohesive, networked force despite their distribution through physical space-time. This research project works to understand how to best enable cohesive combatant-sensor integration for DMO and to model and outline the system capabilities and behaviors necessary for their integrated implementation.

Keywords: *distributed maritime operations, DMO, autonomy, combatant-sensor integration, simulation*

Background

As technologic sophistication continues to advance rapidly, a wide array of diverse robots, unmanned vehicles, and other intelligent systems continue to demonstrate unprecedented capabilities for extended, independent, and even collective decision making and action. Indeed, the technologic capabilities of many autonomous systems (AS) in operation today exceed the authority delegated to them by organizations and leaders. In many skilled mission domains and demanding environmental circumstances, AS can outperform their human counterparts along many dimensions, yet they fall short in other ways. Hence, *integrated* performance, by autonomous systems and people *working together*, is superior in an

increasing number of circumstances. This increasingly important phenomenon is referred to as *teams of autonomous systems and people* (TASP).

Such collaboration between autonomous systems and people represents an important element of DMO. Available manned and unmanned, surface and air, combatants and sensors require integration to serve as a cohesive, networked force despite their distribution through physical space-time. Such integration represents a considerable technical challenge and is distributed organizationally as well; that is, combatants and sensors are distributed across different organizations in addition to physical space-time. Cohesive combatant-sensor integration represents a considerable command and control (C2) challenge also, as a variety of different platforms, services, and even nations are likely to assert simultaneous control over the diverse combatants and sensors.

This research project works to understand how to enable cohesive combatant-sensor integration for DMO and to model and outline system capabilities and behaviors necessary for their integrated implementation.

Findings and Conclusions

The research questions are pursued through the following major project tasks:

- Task 1: Research the academic, doctrinal, and professional literatures to understand the current state of the art and future trajectories of unmanned systems and DMO.
- Task 2: Identify and adapt a computational model to characterize the structure, behavior, and performance of manned and unmanned systems in DMO organizations.
- Task 3: Simulate the comparative structure, behavior, and performance of maritime operations today.

Key findings center on our successful establishment of a computational model to characterize the structure, behavior, and performance of DMO organizations. A state-of-the-art organization simulation system, developed originally at Stanford and validated over nearly three decades, is selected and employed to model a joint task force (JTF) conducting maritime operations. This JTF model is specified to represent a collection of current Navy platforms (e.g., carriers, destroyers, littoral combat ships) and both manned (e.g., F/A-18, MH-60) and unmanned (e.g., ScanEagle, Fire Scout, Triton) aircraft conducting intelligence, surveillance, and reconnaissance (ISR) missions. The JTF ISR model establishes a powerful baseline for comparison with alternate DMO organizations and approaches.

Key findings center also on simulation results produced by the JTF ISR model. Such results reflect an experiment design comprised of 24 different conditions, each specified with a unique computational model instance, simulated 50 times, and measured across a panel of eight performance variables. The degree of autonomy, level of interdependence, and organization of maritime operations all exert major effects on simulated JTF ISR performance. The results provide a huge and rich set of data and information that will be invaluable for examining and comparing alternate DMO organizations and approaches.

Recommendations for Further Research

We recommend future work to continue along the lines of this project. Specifically, the JTF ISR model can be extended to represent one or more alternate DMO organizations and approaches, which can be simulated to produce performance results for comparison with maritime ISR operations today.

The most promising DMO organizations and approaches can then be examined in greater detail, through laboratory experimentation using experienced naval officers and sailors, the results of which can then be examined in turn through operational testing onboard aircraft and ships at sea. Future research can also examine alternate missions (e.g., strike, air defense, surface warfare) that extend beyond ISR.

NPS-19-N119-A: Sociotechnical System Evaluation of Naval Aviation Policies, Guidance, Training Events, and Training Systems

Researchers: Dr. Karen Holness and Mr. Brian Wood

Student Participation: Ms. Michelle Gilbert CIV, Mr. Joshua Gould CIV, Ms. Kayla Seymour CIV, and LCDR Claire Dyer USN

Project Summary

As a follow-on to Naval Research Program (NRP) Naval Postgraduate School (NPS) NRP-NPS-18-N142, which proposed sociotechnical system (STS) requirements for improved F/A-18 Strike Fighter Advanced Readiness Program (SFARP) flight training events (FTEs), this project:

1. Examined the alignment between relevant F/A-18 organizational, training, and systems engineering processes for various F/A-18 FTEs beyond SFARP that revise or create requirements
2. Identified alignment gaps
3. Recommended alignment improvements

These tasks were accomplished using a combination of model-based systems engineering (MBSE) analysis methods, qualitative data analysis (QDA) methods, and data from subject matter expert (SME) interviews. The project principal investigator (PI) and the systems engineering (SE) capstone project team used the SME interview data, QDA, and MBSE to identify a primary gap in how training system utilization and effectiveness data are collected, analyzed, and used to support training system requirements development. To address this gap, we proposed a tool to improve the identification of policy alignment gaps and develop SE training system requirements. The proposed tool's functional requirements and a system architecture were modeled using Microsoft Visio, PowerPoint, and the MBSE software, CORE. Also, documents relating to F/A-18 SFARP training were loaded into the Lexical Link Analysis (LLA) software by the project Co-PI and Information Sciences (IS) thesis student, to uncover and graphically display relationships among these documents. This demonstrated the use of LLA as a potential part of the recommended system architecture for policy document analysis. Additional feasibility assessments for creating and implementing the proposed SE tool are recommended as future work.

Keywords: *naval aviation, flight training events, requirements, sociotechnical systems, systems engineering, qualitative data analysis, information sciences, Lexical Link Analysis, LLA*

Background

STS requirements address technological, organizational, and environmental interactions. The NPS-18-N142 research project evaluated aspects of the current STS used to conduct F/A-18 SFARP flight training events (Holness, 2018; Bee et al, 2018). Emphasis was placed on:

1. Interactions between hardware, software and people
2. Corresponding processes to support these interactions

That project identified system capability needs, proposed corresponding technical and social requirements, and recommended improvements to the STS and the conduct of training events. The goal of the NPS-19-N119-A study was to evaluate the organizational and environmental STS interactions necessary to engineer and implement an improved STS design not only for SFARP events, but also for various F/A-18 flight training events. According to Dan King from the Naval Air Systems Command (NAVAIR) Mission Engineering and Analysis Department (4.0M), who provided the initial concept for this FY19 project, “The cross-organizational complexities of training often result in a lack of alignment between system engineering activities and fleet administrative/training activities when it comes to warfighting capabilities and readiness priorities” (email with NRP proposal inputs to author, August 24, 2018).

Based on this initial perspective, the following research questions were identified for this project:

1. What policy gaps exist between Navy/NAVAIR SE policies and Navy training and readiness policies?
2. Do JCIDS-identified capability requirements correlate with current Navy training and readiness policies, training events, and Navy/NAVAIR SE policies?
3. How should requirements and policies from across different Navy/NAVAIR organizations align to create an improved F/A-18 flight training event STS?

Key focus areas included traceability among the following:

- relevant training and SE policies,
- implementation of these policies,
- corresponding training requirements,
- corresponding training system requirements,
- the implementation of SE efforts, per current SE process, to realize these requirements,
- the inclusion of material readiness information in the SE process,
- the planning and scheduling of training events.

Based on the project’s initial premise, the primary hypothesis was that traceability between the above focus areas was not clearly and consistently evident across relevant Navy/NAVAIR SE policies, and Navy training and readiness policies.

Findings and Conclusions

An in-depth evaluation of the current internal and external systems that influence the planning, resourcing, and execution of F/A-18 FTEs was conducted, including an assessment of policy, guidance,

requirements, and organizational interactions. In the first quarter of the project, a key capability gap was identified through:

1. Discussions with N98 and NAVAIR 4.0M
2. An initial review of four key SFARP documents
3. Using the results of one SME interview in December

A data collection and analysis gap between training performance data, training system utilization and effectiveness data, and policy/guidance/requirements alignment was clearly defined in January 2019. Exploration of additional evidence to further characterize this gap and to discover other alignment gaps guided the QDA, MBSE, LLA, and SME interviews during the remainder of the project from February through August 2019.

A total of eighteen (18) training-related documents were analyzed between the PI, Co-PI, and student researchers for this project. The PI and SE capstone students used Microsoft Excel and Word to conduct a basic QDA analysis that categorized relevant text segments. The results were then evaluated for linkages between data collection and analysis of training performance data, training system utilization and effectiveness data, and policy/guidance/requirement revision or creation. The PI also evaluated an additional five (5) SE related documents, using Excel, Word, and the commercial off the shelf (COTS) QDA software called ATLAS.ti.

The key QDA results revealed the lack of data analysis to support correlations between training performance data, training system utilization and effectiveness data, and documented policy/guidance/requirements. Key variances in the execution of FTEs (e.g. flight waivers, equipment substitutions, etc.) also added qualifiers to the data that impacted SE requirements development, but were not clearly and consistently tracked across the board. A personnel gap between the SE at the Program Office level and the data collection sites was also identified. Even though a variety of periodic training requirements and training system requirements meetings are held, there are no dedicated personnel who can accumulate and evaluate these particular data types to support SE assessments.

In light of these findings, an SE Assessment tool, process, and personnel structure was proposed. The SE capstone team focused on a version of this tool just for SFARP. They identified two possible tool configurations, modeled them in the Microsoft PowerPoint and the MBSE CORE software, and compared them using a multi-objective decision analysis process with pre-determined evaluation measures. The recommended alternative, which received the highest score in this analysis, creates dedicated SE analyst roles within the Naval Aviation Warfighting Development Center organization. This person/team performs the proposed data correlations, and generates training system and training requirement recommendations.

A greater cross-organizational version of the SE Assessment tool, process, and personnel structure was proposed by the PI to cover the gamut of F/A-18 FTEs. These were modeled in Microsoft Visio and CORE. Three SME interviews were also conducted by the PI in July 2019, to solicit inputs on the appropriate data types and organizational users of the proposed tool.

The key results from these interviews indicated a desire to have access to as much relevant data as possible, in order to generate verifiable evidence to support proposed training and training system requirements. Parallel to the SE work, the LLA was conducted by the Co-PI and IS thesis student on the same 18 training-related documents from January to August 2019. As defined by Zhao, Gallup, & MacKinnon (2013), “LLA is a form of text mining in which word meanings represented in lexical terms (e.g., word pairs) can be represented as if they are in a community of a word network” (p. 4).

Using LLA, it was determined that documents relating to SFARP issued at adjacent level Echelons, had a higher level of fit than those issued at more than one Echelon level apart. Thus LLA could be used to examine intent between different Echelons of documents. LLA produced data taken from these documents in the form of word pair (or bigram) matches between documents. This data was also used to confirm this assessment using Pearson Correlation Coefficients. The one outlier was that the strongest fit by Echelon 4 issued documents with Echelon 2, and not Echelon 3 or 5.

The initial hypothesis was that LLA would be able to determine if there was a fit (and thus a relaying of intent) between higher and lower level documents. But, because higher level instructions are at the macro level and lower level ones are focused at the micro level, this hypothesis was determined to be less valid when the two issuing Echelons were more than one level apart, and even more so as the gap widened. Additionally, word pairs from each document were compared with other documents to determine their degree of usage. Bigrams that did not have a high Match Consensus rate could be examples of gaps between the documents, and therefore, further study in this area could be done as follow-on research.

Including a software tool like LLA or a COTS QDA software like ATLAS.ti, within the proposed SE Assessment tool, will allow requirements developers in the F/A-18 training and SE communities to evaluate policy and guidance document alignment with system performance specification and other hardware/software requirement documents. This is important to identify and mitigate potential conflicts before and while performing SE, in order to design/build/test and install system modifications, upgrades, or new system developments. Considering the number of organizations that provide inputs to the execution of training and the development of training requirements and system requirements, this deconfliction task is a key STS requirement to ensure consistency and alignment between organizational processes design to support the same SE objectives.

Recommendations for Further Research

In the standard Department of Defense acquisition lifecycle, the design/build/test effort for the proposed SE Assessment tool is in the early phases, pre-milestone A. Therefore, further research is needed to solicit other applicable tool requirements from stakeholders within each organization that would benefit from this tool. Next, the identification of candidate databases, analysis software programs, and networking infrastructures, to actually build the allocated and product baselines for this tool, is also required to progress through milestone B and C. Considering the amount of data and the different data types expected to be used by the proposed SE Assessment tool, high fidelity data mining and data analytic solutions should also be explored. Finally, studies to evaluate feasibility of this tool for other aircraft platforms and the creation of a more general application SE assessment tool is also recommended.

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

Researchers: Dr. Shelley Gallup, Dr. Fotis Papoulias, CAPT Jeffrey Kline USN (Ret.), Dr. Johnathan Mun, and Mr. Brian Wood

Student Participation: No students participated in this research project.

Project Summary

This analysis focuses on the need for lightly manned autonomous combat capability (LMACC) and concepts of operations that require it. LMAAC, as developed in this project, is both an old (corvettes of WWII) and new idea in which autonomy is put into service with Sea Hunter and the LMAAC in Sea Fighter, working together. Rather than building a new ship class from the keel up, this project's concept takes a ship design already in use and redesigns it with the ship maintenance, operations, sensor integration autonomy now in use on Sea Hunter. It adds the very reduced manning to Sea Hunter necessary for decision making above and beyond autonomy. The basis for this study is the *Cyclone* class (Patrol Coastal PC), with potential refinements in propulsion, bow and stabilizer redesign, and novel concepts for fuel loading that support long missions.

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

Background

Small ships have historically been designated corvettes, and became a very important part of force structure during WWII. Many were built by the U.S., but sent to Great Britain as part of the Lend Lease program to help defend convoys. Riverine patrol craft were highly effective in the Vietnam War; however, as the Navy moved into the '80s these craft were largely sidelined or taken from service, as were the PG classes such as USS Gallup and the USS Pegasus. Numerous other concepts were discussed but were primarily for use by the Coast Guard. The *Cyclone* class coastal patrol ships were designed primarily for the Special Warfare Community but shifts in concepts of operations left these ships without a definable mission. A trade was made to the U.S. Coast Guard but those ships were returned to the U.S. Navy for use in specialized missions in the Middle East. In 2006, there was renewed interest in small vessels as part of a force structure that would be able to be in a "constabulary role" (RAND, Small Combatant Ship

Alternatives briefing, March 2006) of peace keeping in concert with other allied navies. In 2014, Naval Sea Systems Command (NAVSEA) produced a very detailed briefing “Concept Design Considerations for Small Surface Combatants” (SEA 05D1, April 23, 2014, Carderock Division). This briefing compared the engineering parameters for small ships in active roles in the first and second island chains. At the Naval Postgraduate School (NPS), campaign analysis of different scenarios provided data and evidence of the potential of small combatants as technical injects to simulations with positive results.

The advent of autonomy has been realized in the Navy’s first autonomous vessel Sea Hunter. This vessel is a test bed for algorithms that maintain the vessel’s safety from collision at sea, but operational concepts have eluded precise definition. The concept of human-machine teaming has meanwhile been developed and concepts of operations are being formed in that role. However, at present this still puts the autonomous vessel in a “sparse control” mode of operation, in company with larger ships such as a guided missile destroyer (DDG).

It is the hypothesis of this study that a small combatant of approximately 1000 tons and manned with very few personnel, could become an effective human-machine team and allow autonomous vessels to range more freely, making it much more difficult for an adversary to target a manned vessel. The crew would essentially be riding an autonomous vessel, where the vessel takes care of itself, that is equipped with the same autonomy as its smaller vessels in company and would be armed with surface to surface missiles, guns and torpedoes. Each of these Sea Fighter ships would be optimized for one or two mission areas. By combining these sea fighting “packs” considerable pressure could be maintained on the first island chain in the Pacific power competition, allowing second island defense to be the domain of the larger capital and multi-mission ships.

This report takes into consideration some of the challenges of this concept but maintains that these can be overcome, and that what is produced are ships of just over 200 feet, approximately 1000 tons, captained by senior post department head O-3s, and with a crew of approximately 15 personnel. These ships would be fast, enduring, and armed to fight, for much less funding than is currently planned for the next generation DDGs or Frigates.

Findings and Conclusions

Cost factors are being gathered to create a total ownership cost simulation of this ship. Data for this effort is still being collected and will result in a Defense Acquisition paper that has already been accepted. Similarly, engineering of this vessel is still being considered for a variety of factors that will make it possible and will use up-to-date technologies such as diesel-electric hybrid propulsion with reversible blades.

There is some analogy here to fighters in the aviation community. When needed, aircraft such as the A-4 Skyhawk were built quickly in response to the need for a carrier-launched ground-attack jet. Fast, agile, and well-armed, it became a very important part of the carrier force structure. Stretching the analogy further, its range was improved by adding drop tanks. Is it possible to add external tanks to these ships that are detached in combat? New ideas will emerge as design work in systems engineering gets underway. Testing of concepts will continue in the campaign analysis course at NPS and in a specific simulation system now in use that tests concepts of automated ships using the same software employed on those vessels.

Recommendations for Further Research

Further research in ship design and employment of human-machine teams in combat will need to be conducted; this research provides an alternative to the present force structure decisions now being considered.

NPS-19-N169-A: Organizational Assessment of a Future Surface Force Development Squadron (SURFDEVRON)

Researcher: Dr. Shelley Gallup

Student Participation: LT Timothy McDaniel USN

Project Summary

To address a faster paced, more complex, and increasingly competitive security environment, the Surface Force needs new or improved capabilities to attack, deceive, and defend against adversary ships, aircraft, missiles, submarines, cyber, and electronic attacks. Additionally, it requires more agile acquisition practices, enabling a rapid and iterative approach to improving performance. To deliver these capabilities, the Navy intends to establish a Surface Development Squadron (SURFDEVRON) as an interface between the research community (e.g., Office of Naval Research, Defense Advanced Research Projects Agency) and the fleet. This interface is necessary in order to coordinate the at-sea testing of advanced technologies and their associated tactics, techniques, and procedures, accelerate the integration of new technologies onto manned and unmanned afloat platforms, and manage the cultural change required to integrate unmanned systems into the surface force. The SURFDEVRON intends to be the Surface Force's tactical development authority for all manned-unmanned teaming efforts, to include advancement and integration of autonomous systems. This will not only increase the speed-to-fleet of new technologies to address capability gaps, but will also buy down risk for Future Surface Combatants. The purpose of this research is to assess the plans for SURFDEVRON organization, and interactions with processes important in Surface Force test and evaluation, and experimentation.

Keywords: *Naval Surface Forces Experimentation, field experimentation, organization design, unmanned systems development, Surface Development Squadron, SURFDEVRON, Trident Warrior, surface combatants*

Background

The concept of a development organization to meet surface fleet needs has existed in different forms for decades. However, now there is a greater need to embrace this concept, given the advent of new technologies, operational concepts and unmanned systems. At the outset of this project, there were questions about the organizational construct of the SURFDEVRON. To be successful, this enterprise needs all platforms acting together as a means to test, which brings in administrative and operational control issues. In addition, there are myriad processes and systems associated with modifying or adding new technologies to warships. In the past, processes such as Shipmain and computer/network approvals have been very difficult hurdles to overcome in fleet experimentation. For example, large-scale surface-ship experimentation venues such as Trident Warrior could take up to 18 months, and involve the work of dozens of subject matter experts and administrative personnel. The SURFDEVRON seeks to support

experimentation but at a much faster pace, resulting in many aspects of managing, testing, and experimenting aligning more efficiently with the purpose of this organization. It should also be noted that for approximately half of this research effort's allotted time, the decision to create the SURFDEVRON had yet to be approved. On approval, the initial staff moved quickly to begin defining the organization and its roles.

As additional background, other communities of the Naval service are engaged in similar development activities. For example, the Submarine Development Squadron and the Air Testing facilities at China Lake and Patuxent River have garnered community support, and conduct extensive testing of new materiel and process (Concept of Operations) research and testing.

Findings and Conclusions

The overall study had three broad questions/goals:

1. What other development groups are performing similar roles and how are they successful?
2. Provide qualitative/quantitative analysis of SURFDEVRON homeport options based on existing infrastructure, facilities, port services, etc.
3. Determine organizational values and principles that will create a culture of innovation, experimentation, and initiative.

This research provided input to the discussion regarding the organization and roles specific to SURFDEVRON experimentation, and to that end, recommendations have been incorporated into the organization. The research did not make recommendations related to homeporting, a decision reached along with overall SURFDEVRON approval. In addition, a student thesis was completed using a total-ownership cost model focused on personnel requirements.

In terms of research question two, qualitative and quantitative analysis of SURFDEVRON homeport options revealed the following: difficulty with a surface development squadron are many and include a lack of standardization across the fleet, a lack of opportunity to detail a ship for significant periods of time during increasing demands for surface assets (even within ship classes), unclear objectives, little means to determine how an experimentation requirement will help close a warfighting gap, and a lack of formal organizational intention dedicated to experimentation. The closest organizational example for fleet experimentation is the Trident Warrior series, which is discussed at some length in the final report.

As this is a multi-year effort with research ongoing into 2020, research regarding questions one and three above will be addressed in next year's report.

Recommendations for Further Research

As a follow-on project, we are developing a "Practical Guide to Planning, Executing and Analyzing Experiments for the Surface Warrior" give that current instructions and resources about fleet experimentation are written at a much higher level than a fleet action officer can implement. This research is being supported separately by SURFDEVRON.

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NPS-19-N190-A: Cost-Benefit Analysis of Navy Station Search and Rescue (SAR)

Researchers: Dr. Simona Tick, Dr. Ryan Sullivan, and Dr. Robert Mortlock

Student Participation: LCDR Amanda Sciberras USN, LT Bryce Christensen USN, LT Nicholas Mann USN, LT John Blankenship USN, LCDR Tobin Rollenhagen USN, LT Nichalos Everhart USN, and LT Terry Miller USN

Project Summary

Search and rescue operations (SAR) are a key component in maintaining the necessary safety coverage of flights at the Naval Air Stations (NAS) located at Whidbey Island, WA, Key West, FL, Fallon, NV, Patuxent River, MD, and Lemoore, CA. The United States Navy (USN) currently employs the MH-60S multi-mission helicopter at all SAR locations. Due to projected inventory shortfalls in the near future and increasing demand on this aircraft for other operations, it is imperative to examine feasible alternatives for meeting NAS SAR capability requirements. These alternatives may also contribute to reducing operational demand for the MH-60S aircraft. In this study, we conducted an in-depth cost-benefit analysis on whether use of a multi-mission combat helicopter to conduct station SAR is the most cost-effective method when compared with outsourcing SAR components. Our analysis considered the location-specific costs associated with operating a SAR unit (fleet inventory, personnel, maintenance, fuel costs, and operational demand) while weighing the tradeoffs associated with outsourcing. Based on our cost benefit analysis, we formulated tailored recommendations to each NAS. While our recommendations would generate cost savings where only the MH-60S is available, our research found that, when funds are available, using civilian-off-the-shelf (COTS) aircraft would dramatically reduce operational demand on the MH-60S.

Keywords: *search and rescue operations, SAR, cost benefit analysis, cost effectiveness analysis, Navy aviation, analysis of alternatives, MH-60S helicopter, commercial outsourcing*

Background

NAS SAR units use MH-60S multi-mission helicopters operated by highly trained flight crews as first responders for aviators and personnel stationed at NAR. Increasing operational demand due to Littoral Combat Ship Surface Warfare and Mine Countermeasures Mission Package deployments is expected to stress MH-60S capacity in the early 2020s, when MH-60S total requirement will exceed total overall aircraft inventory. To inform the Program Objective Memorandum for 2022, we conducted a cost benefit analysis to identify whether use of a multi-mission combat helicopter to conduct station SAR is the most cost-effective method to deliver those services, particularly when balanced with an increasing fleet demand for capabilities provided by the MH-60S aircraft.

We considered the distinct requirements for station SAR services at Whidbey Island, WA, Key West, FL, Fallon, NV, Patuxent River, MD, and Lemoore, CA. We expected our findings to vary by NAS based upon differences in platforms supported, range geometry, environmental factors, operating parameters, and local policies.

Findings and Conclusions

We used a cost benefit analysis approach, as in Collins and Williamson (2013), to systematically examine the specific operational constraints and costs associated with delivering required current and future NAS SAR capability. We engaged three groups of students (see Christensen & Sciberras, 2019; Miller, Rollenhagen & Everhart, 2019; Blankenship & Mann, 2019), who conducted site visits to each NAS location to conduct identification and understanding interviews, and to collect data on aircraft inventory, manpower and local commercial outsourcing availability.

As we anticipated, the cost savings outsourcing recommendations for delivering SAR vary by NAS location. We estimated the cost savings associated with alternative outsourcing scenarios specific to each NAS SAR and considered the immediate and long-term tradeoffs associated with outsourcing. Based on our analysis, we formulated tailored recommendations to each NAS to generate cost savings. While our recommendations generate cost savings for delivering SAR relying solely on the MH-60S, our research suggested that when funds are available, using COTS aircraft would dramatically reduce operational demand on the MH-60S. Our findings and recommendations highlight the importance of site-specific factors in delivering SAR capability.

Recommendations for Further Research

Further research can identify the most efficient implementation plan for replacing the multi-use MH-60S aircraft with COTS aircraft procurement, should funds be allocated towards a fully contracted SAR. Furthermore, the cost benefit analysis models developed in this study can be used to support a large array of resource allocation decisions for commands in the Navy, or DoD.

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U.S. FLEET FORCES COMMAND (USFF)

NPS-18-N369-A: Shipboard Forecasting of the Ocean Acoustic Environment

Researchers: Dr. James Murphree and Ms. Mary Jordan

Student Participation: LCDR Kelly Byrne USN

Project Summary

Forecasts of the ocean acoustic environment are critical in undersea warfare planning. The forecasts describe spatially and temporally complex acoustic features that require high bandwidth to transmit to at-sea users. But high bandwidth is often not available, especially for submarines. So there is a need for shipboard forecasting capabilities to provide forecasts when communications are limited. We have addressed this need by conducting research on sub-seasonal to interannual methods for forecasting ocean acoustic conditions that have the potential to be used in shipboard production of forecasts. We have analyzed atmospheric and oceanic data sets to identify characteristic variations in ocean acoustic conditions and potential predictors of those variations. We have tested the skill of those predictors in producing forecasts of ocean conditions at leads of one to six months. Several predictors appear to be useful in predicting major variations in ocean acoustic conditions in operationally important regions. We have identified and recommended methods by which these predictors could be used in shipboard forecasting with minimal inputs from onshore centers. In future research projects, we will investigate and test these methods in simulated and experimental shipboard forecasting.

Keywords: *Submarine operations, undersea warfare, antisubmarine warfare, long range planning, decision support, decision making, limited communications, meteorology, oceanography, METOC, shipboard forecasting, long range forecasting, climate variations, ocean acoustic environment*

Background

The US Navy conducts long range planning at lead times of weeks to years for a wide range of activities around the globe. This planning is supported in part by Naval Oceanography products and services that provide information on future environmental conditions and their impacts on the operations of US forces and allies, and potential adversaries. Long range forecasts (LRFs; leads of weeks or longer) of atmospheric, oceanic, and terrestrial conditions are examples of products that support long range planning. In the last ten years, Navy LRFs have been greatly improved via increases in, for example, their spatial and temporal resolution, the variables for which forecasts are provided, forecast lead times, and forecast skill.

These improvements in Navy LRFs will continue in the next ten years as new data sets, models, forecast systems, and production capacities become operational. The new and emerging LRF capabilities will improve long range planning and decision making by providing increased forecast accuracy, spatial and temporal resolution, and coverage (e.g., global, seafloor to space). However, these improvements will not benefit ships at sea if communications are limited or unavailable.

Thus, ships at sea may not be able to use LRF forecasts in their planning when needed most, which is especially the case for submarines. Research is needed to determine how to adapt LRF methods and capabilities to enable efficient shipboard production and use of longrange forecasts (Hartmann et al., 2002).

Findings and Conclusions

We investigated the climate scale variability of ocean acoustic conditions (especially sonic layer depth) in operationally important regions of the ocean. We used atmospheric and oceanic reanalysis data sets to identify regions of both high and low variability in ocean acoustic conditions. We then focused on identifying the regional and global scale processes that lead to high variability. The regional processes we analyzed included surface heat fluxes, surface momentum fluxes, wind stress curl and Ekman transport, oceanic advections, and low frequency internal waves. The global processes we analyzed included climate variations (e.g., variations in the Asian summer and winter monsoon, El Nino – La Nina, Madden-Julian Oscillation, Indian Ocean Dipole, Arctic Oscillation), atmospheric low frequency waves, and teleconnections from remote parts of the climate system. We determined that regional variations in wind stress and heat fluxes driven by climate variations are important in creating regional ocean acoustic variations. Predictors based on these climate variations may be useful in predicting these variations at leads time of one to several months. Relatively straightforward forecasting systems that use these predictors may also provide skillful forecasts that can be generated on ships that have little or no communications with onshore support centers.

Recommendations for Further Research

We recommend that additional research be conducted to better assess the methods we have tested, as well as similar systems that we have not tested. These assessments should focus on the skill of the forecasts, the use of these systems onboard ships that have limited connections to shore support centers, and the applicability of these systems to a range of locations, seasons, and lead times. The skill assessments should focus on how much improvement the forecasts system provide over alternative forecasting systems, while the use assessments should focus on how feasible and effective the recommended systems would be when used in shipboard settings.

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NPS-19-N038-A: F-35 MADL Data Integration for the Surface Force

Researchers: Mr. Victor Garza, Mr. Brian Wood, and Dr. Shelley Gallup

Student Participation: LT Matthew Minnis USN

Project Summary

Multi-functional advanced data link (MADL) allows F-35s to pass critical data to other MADL equipped platforms (F-35s and B-2s) while maintaining its stealthiness. F-35s can pass this data via Link-16, but doing so does not maintain its low probability of detection (LPD)/low probability of intercept (LPI).

US Naval surface units (e.g., guided missile destroyers [DDGs]) are interested in directly receiving MADL data while maintaining a stealth environment. Commander, Naval Surface Forces (CNSF) wants to determine how this problem can be solved. Through this research of various options being considered in closing this gap, such as relaying the data via an intermediary radio or tactical means by specific positioning of F-35s in and out of the airborne operating area, the recommendation of using one of three tactical solutions using the Freedom 550 radio was made as a way ahead for continued development.

A secondary goal of this research effort was to provide a cost-benefit analysis (CBA) of one or more of the proposed solutions. However, organizations were reluctant to participate in this work, however, after initially declining, two groups came on board late in the period of performance. These two CBAs will be conducted in Q1 FY20 and will be included as part of a Naval Postgraduate School master's thesis (LT Matt Minnis) due in June 2020.

Keywords: *multi-functional advanced data link, MADL, F-35, guided missile destroyer, DDG, communications, CBA, cost benefit analysis, TOC, Total Ownership Cost, Freedom 550, surface, distributed operations, JSF, Joint Strike Fighter, Aegis.*

Background

Two types of solutions are being considered in this research: technical and tactical. The majority of the technical solutions involve MADL data being relayed to another radio (e.g., Link-16 supported radio) and transmitted to a third party (e.g., DDG, FA-18, unmanned air vehicle (UAV)). The Northrop Grumman Freedom 550 radio is the centerpiece of all technical solutions, and would be located on a long endurance aircraft, receive MADL data, and relay it to another network for transmission. Due to cost issues the placement of MADL aboard other platforms is not being considered in this thesis. Solutions involving the Freedom 550 radio will provide a technical means to resolve the MADL communications issue. Tactical solutions such as location of F-35s in the battlespace and choosing to ignore LPD/LPI may provide an interim fix while the communications architectures are being developed.

Findings and Conclusions

Methodology

Information was gathered from the various organizations proposing solutions to include papers, articles, and direct communications with key personnel.

Technical Solutions

1. Northrop Grumman produces the Freedom 550 and is proposing to use its Airborne Gateway aboard an RQ-4 Global Hawk UAV as its solution. The Global Hawk has extensive experience acting as a communications node in the Middle East and other locations.
2. The Fused Integrated Naval Network (FINN) is undergoing testing under the direction of George Mason University. The FINN Communications Gateway houses the Freedom 550 in a pod attached to a standard aircraft weapons station on a medium-altitude long-endurance UAV (e.g., MQ-9 Reaper).
3. Rough Babbelfish again uses the Freedom 550 and it would be placed aboard a P-3 (or any long-endurance aircraft [e.g., EP-3, P-8, C-variant, UAV]). In addition, the receiver would accept and display the translated data via Rough Squid and push it to other non-MADL users. Rough Squid

processing and display needs to be more fully developed in order for MADL data to be displayed aboard a DDG.

4. In September 2016, an F-35B sent MADL data to a ground station connected to USS Desert Ship, a land-based facility simulating a ship at sea (White Sands Missile Range, NM). In a live-fire missile event against a UAV, the F-35B demonstrated supporting Naval Integrated Fire Control-Counter Air.
5. In 2015, a Gulfstream II was used as a relay platform between the F-35's MADL and F-22's IFDL (Intra-Flight Data Link). Its terminal contained both.
6. Solutions that share some commonality but did not specifically address the MADL to DDG communications problem.
 - a. Talon HATE is a data link pod developed by Boeing to allow communication of F-22 IFDL data with F-15s.
 - b. In 2017, a Royal Air Force Typhoon fighter successfully communicated with an F-35B via the Freedom 550, receiving MADL messages translated to Link-16 format.
 - c. Project Missouri demonstrated F-22s transmitting (via Link-16) to an F-35 avionics test bed at a ground station in 2013 and in Northern Edge (2017). A Rockwell Collins radio (for Link-16 and L-3 Comm devices) was used in the event.

Tactical Solution

In 2017, Brigadier General Scott Pleus, USAF, Director of the F-35 Integration Office, proffered a tactical solution. F-35s would be stationed inside defended airspace and transmit data to another F-35 outside of the space. That F-35 would then transmit to another aircraft via Link-16 which would forward the data to other recipients (e.g., DDGs). The LPI/LPD of the interior F-35s would be maintained while MADL data would be sent to an outside requesting platform.

Another solution to be considered is not using MADL when non-MADL participants are involved in the effort and transmit data directly via Link-16. Although the F-35's LPI/LPD would be degraded at this point, it is a viable option when planning a mission, since the crew will know the risks involved.

Findings

The use of a tactical solution using the Freedom 550 radio appears to be the primary path to success. Three major efforts to resolve the problem are in work and should continue towards a viable solution. In the interim, a tactical solution of bypassing MADL transmissions by using Link-16 remains an option.

Recommendations for Further Research

The CBA will be completed by December 2019 and included in LT Minnis' thesis. In terms of additional research, CNSF should continue to monitor each of the major technical solutions being considered, while also reviewing lessons learned from F-35 deployment use of Link-16 vs. MADL.

NPS-19-N062-A: Diesel Submarine Support to SOF

Researchers: Dr. Geraldo Ferrer and Dr. Simon Veronneau

Student Participation: LCDR Clifford Rivera USN, LCDR James M. Steele USN, LCDR Long K. Tran USN, LCDR Malcolm L. Elliott USN, LCDR Shannon E. Percival USN, and LT Jonah A. Petrinovic USN

Project Summary

Maintaining a forward-deployed presence world-wide is integral to the mission of the Department of the Navy (DON). To conduct port visits, the Navy uses a network of organic and contractor-furnished assets supplied by foreign companies, in order to provide husbanding services and coordinate delivery of supplies at various ports where an organic footprint does not exist. To assess the implications of using husbanding service providers (HSPs), this research had three objectives: Evaluate the use and demand for HSPs in peace time during routine operations, and during a potential contingency, assess the security vetting of HSPs, and estimate the Operational Security (OPSEC) implications and potential for exploitation by likely adversaries. To better secure the force before, during and after port visits, three alternative courses of action (COAs) are proposed to improve the current operational posture.

Keywords: *Operational Security, OPSEC, husbanding service providers, HSPs, Naval Supply Systems Command, NAVSUP, overseas deployment, contingency operations*

Background

Naval Supply Systems Command (NAVSUP) contracts services for the Navy, Military Sealift Command, Army, and Coast Guard vessels conducting port visits in non-U.S. supported ports. Presently, there are six regional multi-award contracts (MAC) in place that provide worldwide husbanding services, in each area of responsibility (AOR). Under the MAC, many potential suppliers have fair opportunity to bid for a task order awarded for each ship's port visit requiring husbanding services (NAVSUP, personal communication, February 15, 2019). Sound OPSEC practices are important to maintain security and freedom of movement of U.S. forces. Subsequent screening of subcontractors is an important link for maintaining security of operations. Vendor vetting is important to reducing risk in conducting business with third-party and foreign-national logistics providers. Weaknesses in the processes by which contracts and task orders are awarded and shortfalls in contractor oversight and payment processes have been the subject of review by the DON (Naval Audit Service, 2014). Sensitive information passed to HSPs during port-visit coordination presents a vulnerability in security of the U.S. Navy. The Glenn Defense Marine Asia corruption case (Whitlock, 2015) demonstrated the DON's vulnerability in contract management by exposing how HSPs can influence key personnel and compromise OPSEC in theater (Burke, 2013). That incident highlights how easily ship schedules can be manipulated or compromised to benefit an HSP. It also reveals the risks and uncertainty associated with security when working with foreign third-party vendors. Furthermore, during a time of major theater conflict, the logistical challenges of relying exclusively on HSPs can quickly mount to the point where port visits are no longer feasible, compromising the U.S. Navy's mission. Properly compiled, the information passed on to these contractors can provide insight to the type of mission and readiness of the fleet in theater.

Findings and Conclusions

This study followed a multimethod field study methodology combining literature review of unclassified and classified resources, and archival data analysis, as well as semi-structured interviews of subject matter experts. We have high confidence in the reliability of the information and data obtained as part of this process. Two groups of students used these methods to complete two separate master theses (Elliott, Percival & Steele 2019; Petrinovic, Rivera & Tran 2019). We have combined results of these theses and augmented them with our own interviews and document reviews.

This research directly answers the need from OPNAV N4 to investigate the OPSEC considerations of HSPs and their implications for the entire spectrum of the naval forces deployed overseas. It fills a need to evaluate the consequence of using foreign HSPs supporting our fleet worldwide.

This research found that there is not a standardized robust security vetting process in place for conducting business with HSPs (NAVSUP, interview conducted with authors, March 20, 2019). In the absence of a standard vetting process, contracting officers (KO) are making a responsible determination on the HSP as prescribed in Federal Acquisition Regulation Part 9. Vetting HSPs and gaining a true understanding of a vendor's intentions and background is difficult. They are business/service providers that are not necessarily loyal to the U.S. Their priorities will naturally lie with their native country or with simplifying their processes to increase profits. To better secure the force, this research proposed three alternatives to close this security gap:

4. *Maintain Status Quo*: Maintain the current process with an understanding of the associated risks. Combine the responsibility determination made by the KO with the quality assurance surveillance plan conducted by the contracting officer representative (COR), and Port Visit Feedbacks provided by ships.
5. *Expand Security Requirements*: Expand the current vetting process to require prime contractors to disclose the subcontractors hired to fulfill the port visit task order. The subcontractors would then need to meet the same requirements of database representation and performance documentation as the prime contractor.
6. *Implement a Logistics Support Representative Program*: Introduce a fully vetted U.S. government representative to act as a liaison between HSP, COR and customer to handle sensitive information. This program would be implemented sooner in select ports based on corruption and terrorism indicators, and in regions with greater proximity to near-peer threats.

To support operations in a contingency environment, we made several recommendations. Some of them provide multiple benefits to the U.S. Navy, which is why we believe they should be researched in greater depth soon:

5. *Build our own organic capabilities* in the 7th Fleet AOR and in other AORs as needed. These assets would be better equipped to handle a surge in demand that would be beyond the capabilities of HSPs. It would improve security and it would allow prepositioning of assets required for port visits.
6. *Enhance diplomatic relations with host nations* in all AORs, especially the ones that the U.S. military desires to use for port visits during a major theater conflict. Having other countries as allies would allow the U.S. military to use military ports or preposition organic assets would increase flexibility for the US Navy.

7. *Integrate logistics in the annual wargames* to highlight the challenges of pulling into foreign ports. Simulating poor communications and training supply officers to expedite port calls in such environments would increase everyone's resiliency.
8. *Expand the current vetting process* to require prime contractors to disclose the subcontractors hired to fulfill the port visit task order, as described above. Operations security and the safety of U.S. military personnel depends on understanding the backgrounds of those who work for HSPs. A random audit program is an excellent first step to ensure security.

This study contributes to the body of knowledge on the OPSEC considerations of HSPs. It identifies clear COAs to enhance the operational security of our forces when deployed overseas. Short-term implications are that the U.S. Navy still has an important weakness in its HSP program and that long-term structural changes need to be enacted soon.

Recommendations for Further Research

Future research should focus on how such an organic capability could be created to support the U.S. Navy; identifying the costs and the procedures associated with implementing these recommendations should be prioritized.

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NPS-19-N065-A: Expeditionary Mine Countermeasures (ExMCM) C4I Requirements (Continuation)

Researchers: Mr. Arijit Das and Dr. Sean Kragelund

Student Participation: Maj Pyojeong Kim ROKA

Project Summary

In the mine warfare community, a mission consists of mapping the ocean floor using sonar technology, which is a process that generates gigabytes of files. These files contain the metadata and the sonar images packed in a proprietary version of the TIFF image file format, as specified by the sonar vendor. Mission data has been collected for decades, yet there is no way to catalog, search, and extract analytics from historical information. Using the Java programming language and a Hadoop Distributed File System (HDFS) cluster of servers, the Naval Post Graduate School (NPS) managed to extract information and store it in a not only SQL (NoSQL) database (HIVE). Using a HDFS-to-Oracle database data transfer tool (Sqoop), a subset of the data was then moved to a relational database schema which opened up the ability to combine with Google Maps. Integration of the visualization (maps) and search was provided by the database vendor add-on known as Application Express (APEX).

Mine identification is a separate research project that involves analyzing the image portion of the file, and is a major Navy effort. The NPS-computer science (CS) team explored artificial intelligence (AI) algorithms for mine identification, and were encouraged by the results (research in progress). Given the cost overruns of any project, the team also demonstrated that the needed hardware/software can be assembled and installed to build a cost-effective system using open-source technologies.

Keywords: *ExMCM, C5I, unmanned underwater vehicle, UUV, Sonar, Java, Hadoop Distributed File System, HDFS, Hiv*

Background

The mine warfare community uses many laptops during each mission, which prompted the NPS-CS researchers to look into ways of reducing the computer hardware footprint. The key finding in the FY18 NRP research effort was the fact that a typical mission generates 1000s of files (gigabytes of data), which are then divided over several laptops for manual mine detection.

NPS-CS researchers suggested using a HDFS server cluster computing solution (divide and conquer strategy) to automate the process of mine detection. Since automatic image detection is already an ongoing Navy research topic, the NPS team was asked by the sponsor to look at ways to organize the historic mission data (sonar), and suggest new technologies for consideration. Data is constantly growing so one should be cognizant of hardware and software costs (storage of the data). With this in mind, the team explored HDFS (scalable system software) to extract the metadata from the files and store it in a NoSQL (scalable) database HIVE. Data was transferred from HIVE on HDFS to Oracle on a single server using Sqoop, since the community is more familiar with SQL as a relational database (Oracle is part of the Navy license). The team then looked into an interface to display the data on Google Maps using APEX, included in the Oracle database license. In any project, cost is a major consideration, which the team needed to be aware of at all stages.

AI algorithms are currently being applied to analyze image data, but AI is not an easy topic for the average end user to fathom, so the NPS team looked at narrowing down the thousands of algorithms to a few that were applicable to mine detection. Finally, consideration was given to building a hardware/software platform for this project, using a mix of old and new computer hardware, open-source software, and Department of Defense (DoD) vendor licenses, which will also be cost-effective.

Findings and Conclusions

As a first step, the NPS-CS team requested sanitized data from Dr. Kragelund's unmanned underwater vehicle (UUV) lab and the Mine Warfare School in San Diego. UUV MOD-2 sonar data was provided which was stored in the campus knowledge portal SAKAI. The sonar vendor Marine Sonic Technologies provided the format of the file (open source) which was used to write Java programs for extracting the data.

The sonar data contains metadata information like timestamps, latitude, longitude, and depth. The data is stored in a binary format and needs to convert into clear text, and the image is stored in the industry standard Tagged Image File Format (TIFF) format, therefore, every sonar file has 2 parts, the metadata and the TIFF sonar image. Java is a programming language that provides libraries to read binary data and transform it into human readable format, which is why it was chosen for this project. Java is also available as an open-source product with no licensing needed for research and education.

The first version of the Java code was written on a laptop and this allowed the team to understand the details of the file format and the code logic well, and to help debug it. The mine warfare community data is constantly growing, so a laptop, desktop, or even a single server will not solve the challenges. What is needed is a scalable operating system software, where one would write the code once and let the system handle the scaling (data growth). Thus, the team chose HDFS which is also an open source product and can be installed by a person with a CS background.

The laptop Java code then was transformed to the Java version for HDFS, as there are differences between the two in terms of what libraries need to be used. To test the code, the sanitized sonar files were moved to HDFS and the code was run against it. The metadata was separated out and stored in the file system. The end-user community cannot be expected to write Java code for HDFS, so the data was next loaded into HIVE. HIVE is a scalable DB on HDFS and one can search using SQL (no need to write Java code).

Since HDFS is a Big Data platform, the amount of data in HIVE is difficult to plot or visualize. Therefore, a subset of the HIVE data was moved to an Oracle DB running on a single server. Sqoop, which is also an open-source tool, was used to move the data from HDFS to Oracle. It is expected that the Oracle DB will ably handle this smaller-sized data. Data by itself in a DB table has no meaning until one can search and visualize it, so for this the team used APEX to integrate the DB data to Google maps. This provided the coordinates of each mission in a localized manner, and the ability to narrow down the data sample makes it more manageable and easier to work with.

The mine warfare community uses software to manually search the sonar TIFF files for mine locations. The team next looked at how to use AI algorithms to automatically detect a mine in an image file. However, this effort is a work in progress, and is not ready to be integrated into HDFS. The AI algorithms use the clustering methods based on two common techniques, namely K-means and DBSCAN. A mine is identified by a bright spot and a shadow, which was the basis of the algorithm

developed by the team. The image was separated into smaller-sized frames, and in the first iteration bright spots were tagged, and in the next iteration dark spots were tagged; frames that had both were tagged as potential mine locations.

Finally, the NPS-CS team asked, if the Navy were to use these ideas in its day-to-day workings, what will be the cost footprint? There are two aspects to this problem: first, at the end of a mission the file sizes are in the gigabyte range, and can be analyzed by a small-sized HDFS cluster that can be packed into a pelican case and transported to the UUV location. A smaller cluster is within the budget and can replace the need for multiple laptops, and when loaded with the code will provide the automation needed. The goal is to provide an assistant to the operator that can save time in detecting mines, leaving the final decision-making to a human. The other goal is to catalog the historical data which can be in the many terabyte range, and for this a larger budget needs to be allocated for hardware, software, and an information technology (IT) team. The servers need to be made complaint to the information assurance standards of the Department of Navy and DoD. The historical data is probably dispersed amongst various servers geographically, so gathering all of that will need some logistics planning.

Recommendations for Further Research

NPS is an academic and research institution, and given the funding amount for this project the NPS-CS team can only apply its learning and test out a few new ideas. To convert this effort into a working product or prototype, one needs to have a bigger budget, staffing, and longer-term support. The team managed to demonstrate the application of HDFS, AI, and DBs to aspects of the project, but one will need to integrate them using more software development. Once a version 0 platform is built, the mine warfare community can then test its ideas and help fine tune it. This phase will involve the subject matter experts working with the IT team to make a real-world solution.

NPS-19-N067-A: Naval Surface Warfare Center (NSWC) Lessons Learned Program (Continuation)

Researchers: Dr. Shelley Gallup and Dr. Erik Jansen

Student Participation: No students participated in this research project.

Project Summary

Our research employed a cross-organizational data collection survey for Naval Surface Warfare Center (NSWC) Lessons Learned improvement. We used outcomes of the most current (FY18) qualitative study to construct a NSWC-wide survey instrument. The project included creating that instrument, distributing it among contractors and conducting interviews, analyzing the data gathered, and providing results back to the NSWC. In parallel, some research was conducted on a range of advanced technical means without a final recommendation, and will become part of the upcoming year's effort.

Interviews with potential user personnel indicated that the knowledge system embodied in lessons learned is more of an organizational requirement than a tool for re-use of knowledge. The current system is primarily for the use of after-action reports (AARs), required after training events. Therefore, the Lessons Learned Program (LLP) is primarily seen as a means to document training and issues related to training,

and less as the means by which lessons learned in actual operations are recorded. In addition, the organization of the LLP and knowledge management are largely detached. In both, if users have queries and want to know facts, they have to work through the knowledge manager and the LLP manager to conduct research related to the question. Other users are trained to do such work, however, the LLP system in particular is difficult to use, and requires access to Secure Internet Protocol Router. Therefore, results are usually in the form of multiple documents, requiring further research to address the question.

Addition of new information such as AARs into the LLP requires that they pass upwards through the chain of command. Only when approved by the commanding officer is the AAR returned to the LLP manager to be uploaded into the database. This centralization of effort at the staff level precludes full participation of the users at NSWC, whom are distributed globally and engaged in real world operations. Additionally, knowledge flows through the LLP are low power (Gallup & Jansen, 2018) primarily due to the time lag in the system. Knowledge flows through the informal system (e.g., turnovers between teams during relieving in-country) have very high power, but is limited in reach.

The results of this year's effort support the theory that, to be useful, lessons learned need to be spread across the organization. In terms of knowledge flow theory, this is a matter of increased "reach." Access to the information and the ability to add data are critical to a successful program. Without these functions and a centralized system where information is archived, disparate users have little incentive to use what is available or add new information.

This is a continuation project with one year left (2020), and is focused on making the LLP more useful throughout the NSWC community. This data is concurrent with a similar project with Office of the Chief of Naval Operations (OPNAV N1) to improve knowledge management throughout it

Keywords: *after-action report, AAR, Knowledge Flow Theory, KFT, lessons learned, Navy Lessons Learned Program*

Background

LLPs have been implemented in different forms across the US military for decades. The US Navy's version of the LLP was initiated in 1991, and developed through the 90s, with limited success. Oversight responsibility for the program was given to the newly commissioned Naval Warfare Development Center (NWDC) in 1998, when a formal instruction was created and distributed, mandating the program at the unit level and up. Since, there has been adaptation of lessons learned on multiple information technology platforms and focus on the specific and unique needs of navy organizations. In other words, the Navy Lessons Learned Program (NLLP) is less of a centralized repository and more a series of independent systems adapted to local needs; the NSWC is one such command.

Our working hypothesis was that improved performance of the LLP will create knowledge re-use from the past and add an operational dimension to the LLP that does not currently exist. As improvement in the access and quality of the knowledge occurs, users will be drawn to its usefulness. Shortly after its deployment by NWDC, the role of lessons learned in a learning organization was explored (Garvey, 2001) outlining the intended structure and management of the NLLP; findings indicated the organizational structure was in place, but was largely not used.

Findings and Conclusions

As this is the second phase of a three-year project, developing recommendations is a bit premature, with the exception of having identified objectives and methods to employ in the upcoming third and final year of the project. We can say that knowledge conservation for reuse, such as knowledge management and LLPs, are of increasing interest to organizations. Motivations include saving knowledge in spite of personnel turnover and knowledge loss (tacit knowledge), and improve competitive advantage. However, tools for archiving, exploring, and making knowledge useful in a current context are lagging, which is especially true in cases with time limitations. In this project, the use of organizational models assisted in understanding the intertwined nature of knowledge and organization; separation of these processes does not seem to support organizational goals, as it creates further distance between user and data.

As this project has continued, additional research initiatives have been launched by other organizations, which are essentially asking the same questions. Therefore, it is possible that we are entering an era in which lessons learned and general knowledge will be combined and made available through updated technology (e.g., artificial intelligence). so further exploration of this research aspect is recommended.

Recommendations for Further Research

Further research should include a design challenge event to include users, technical providers, and knowledge managers, along with acquiring a data set for development and application of machine learning and natural language processing.

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NPS-19-N074-A: Effectiveness of Training Systems that Employ Virtual Reality, Augmented Reality, and Touchscreen Displays

Researcher: Dr. Amela Sadagic

Student Participation: No students participated in this research project.

Project Summary

The recent emergence of low-cost, commercial off-the-shelf virtual reality (VR), augmented reality (AR), touchscreen displays, and a variety of input devices, have raised the interest and hopes of stakeholders in many domains. The existence of those devices is the fundamental basis for addressing the training needs of a large number of potential users; candidate groups in the naval domain are enlisted personnel who attend a variety of courses in A and C schools. A prominent gap that still exists in the training domain is concerned with the mapping of those novel technologies, their sensory modalities, and technical capabilities with the specific needs of the trainees.

Those user needs include: the type of skills to be acquired, desired proficiency levels, retention rates, standards of performances to be reached, optimal forms of delivery, and throughput that should be supported. We conducted a series of research activities aimed at developing a comprehensive approach to filling that gap—our goal was to provide stakeholders with necessary guidance and criteria they can use to select the optimal solution for the training of surface Navy sailors. Our research included a literature review, discussions with stakeholders, visits to schools, and the creation of a guidance tool for the selection of technology in the training system. We gave particular emphasis to benefits that each solution offers, their advantages and disadvantages in the training domain, and the potential issues with large-scale adoption. The work produced a set of recommendations for future training systems optimized for the training needs of surface Navy sailors.

Keywords: *virtual reality, VR, augmented reality, AR, mixed reality, touchscreen displays, haptic devices, training, human performance, diffusion of innovation, adoption of technology*

Background

The interest in capabilities offered by technologies like VR, AR, mixed reality, and touchscreen displays has increased with the emergence of low-cost, mobile, compact, and self-contained systems. While those technologies are not particularly new—the first VR headset was introduced by Ivan Sutherland in 1968—the capabilities needed to support large-scale adoption by prospective users in many domains are relatively new. The needs of the training domain have a range of characteristics that is similar to other domains, but this domain has some demands of its own, including: the robustness of the systems, their low price, availability of high-quality software packages like game engines that are needed to develop applications, high-resolution of displays, low end-to-end system latency, high level of visual realism, realistic and validated models of behaviors needed to simulate conditions, and situations for learning and training purposes, a rich set of sensory modalities supported by the systems, interactive modalities that are well suited for the tasks, and intuitive user interfaces. The choice of the optimal combination capable of supporting the needs of large numbers of users in learning and training domains is driven by many factors, that include not only the characteristics of the technology and user interfaces (Sadagic, 2016; Sadagic et al., 2019), but also the form and a scope of those systems, whether fully-fledged simulators or part-task trainers (Greunke, 2015; Attig, 2016; Greunke, 2016; Arthur, 2017; Gibson, 2017; Rashid, 2017; Menin et al., 2018), as well as instructional strategy embedded in those systems (Vogel-Walcutt et al., 2013).

Findings and Conclusions

Our research included a review of user studies that examined different elements of targeted technologies in a learning and training context. A close analysis of the protocols used in those studies reveal three significant characteristics: first, the short duration of the user's exposure to stimuli in the systems that were studied; second, in many studies, a focus on one or two characteristics of technical setups in isolation but rarely on multiple elements in a complex system; and third, a lack of applied studies that involved domain (end) users and instead engaged convenient subjects. Our analysis highlights each of those characteristics in the literature review and identifies the need for future studies.

Our methodology included the following research activities:

1. Literature review: We conducted a comprehensive study of literature in the domain of learning and training relevant to technologies of our interest.
2. Technology market research: We identified representative technological solutions that fall in the category of VR, AR, and touchscreen displays, reviewed their technical capabilities, and commented on their suitability for use in learning and training. We also outlined the domains in which each technology excels.
3. Field visits: We conducted two field visits to schools at naval bases. The institutions we visited were the Center for Surface Combat Systems Detachment West in San Diego, CA, and the Center for Surface Combat Systems in Dam Neck, VA.
4. Data collection: During our field visits, we conducted interviews with multiple instructors. The topics that were discussed allowed us to collect a comprehensive data set that reflects information about the learning and training needs of sailors in their schools, current learning and training approaches, current training results, standards of performance that need to be supported, as well as desired capabilities of training systems.

The resulting technology review also included recommendations for large-scale adoption of technology and guidance for the design of learning and training systems meant to support a large number of potential users. We also provided examples—case studies—with detailed discussion and rationale for the choice of technology and delivery format.

The final elements of our project were centered on guidance and an advisory tool that was designed to help decision-makers and instructors select the optimal technology for training systems. We used the findings from literature whenever relevant sources existed—those were past user studies focused on learning and training, preferably done with domain users. If those were not found, we used general knowledge about a specific technology, including studies focused on human perception. The tool outlined the criteria recommended when selecting technology and designing future learning and training solutions. We also committed to organizing a set of round tables and training sessions with decision-makers and instructors in select schools, designed to introduce the guidance tool developed for the project, and receive further feedback from the stakeholders. This activity will be executed as we confirm the schedule with the leadership in those schools.

The work on this project included advising of several student theses. While the topics of these theses were not directly related to the learning and training needs of surface Navy sailors, those topics examined elements of VR and AR technology, and allowed us to expand our current understanding of the effectiveness of those technologies in supporting the tasks of military personnel.

The following students and their thesis topics were supported by this project:

1. LCDR M. Timmerman: Enabling Collaboration and Visualization of Complex Operational Technology Computer Networks with Augmented Reality Technology. Student graduated in December 2018.
2. LT K. Huntley: Persistent Use of Augmented Reality Technology in Naval Domain: An Exploratory Study. Student is scheduled to graduate in December 2019.

3. Maj B. Knobloch: Military Mission Planning Using Augmented and Virtual Reality. Student is scheduled to graduate in June 2020.

We submitted several manuscripts to technical conferences and symposia; two works were accepted and presented during FY19:

1. de Moura, D. Y., & Sadagic, A. The Effects of Stereopsis and Immersion on Bimanual Assembly Tasks in a Virtual Reality System. IEEE VR 2019, Osaka, Japan.
2. Sadagic, A., Attig, J., Gibson, J., Rashid, F., Arthur, N., Yates, F., & Tackett, C. (2019). Designing VR and AR Systems with Large Scale Adoption in Mind, 14th International Symposium on Visual Computing (ISVC'19), Lake Tahoe.

Recommendations for Further Research

The selection of effective solutions that support learning or training of any group of individuals, including surface Navy sailors, starts with a careful, detailed analysis of the tasks that those individuals need to be able to execute, as well as the skills and knowledge that need to be acquired to execute those tasks. The choice of one solution will inevitably have advantages over an alternative solution, but also disadvantages that may impact human performance once the trainees leave school and start acting in their operational environment. The type of issues that will need to be analyzed include (1) the characteristics of those tasks (time required for the task, nature of the task such as maintenance or operation), (2) the human performance that needs to be supported (targeted proficiency level, performance standards that need to be supported, retention rate), and (3) the domain issues specific to the task (criticality of the task and its impact on operational readiness, expected response time, the number of individuals capable of executing the task).

It is also highly probable that instead of having one solution that supports all user needs, an array of systems will provide comprehensive support for the acquisition of a range of skills and knowledge that the users need to acquire. Additionally, the promise that emerging technologies like VR, AR, and touchscreen displays bring to the learning and training domain will be fully realized if those solutions are reviewed not only for their technical performances, but also for the extent to which they relate to and support the domains that they will serve.

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NPS-19-N079-A: Hydrocode Analysis of Seabed Effector Initiation Options

Researcher: Mr. Jarema Didoszak

Student Participation: No students participated in this research project.

Project Summary

The use of implodable volumes as seabed effectors has shown promise based on past research and preliminary test results, however, their efficacy as replacements for conventional explosives within the desired operational space is yet to be fully determined. Through physics-based modeling and simulation, it was found that the underwater explosion events throughout the design space performed as expected. However, while implosion events generated considerable pressure rise to the surrounding regions at depth, the amount of energy required to overcome the containing vessel significantly reduced the magnitude of the implosion-generated pressure front. Consequently, the collapsible volume required to generate a pressure loading equivalent to an explosive charge was greatly increased. Additionally, there was a time lag and diminishing reach in the radial direction observed in the pressure propagation as compared to the conventional explosive charge. Further study is required into the initiation and response of directionally focused deep-sea implosion-initiated shock fronts, which may overcome the lesser release of omni-directional volumes for an increased pressure loading on target bodies at depth.

Keywords: *underwater explosion, UNDEX, implosion, seabed effector*

Background

An underwater explosion (UNDEX) is characterized by the rapid release of energy from detonation of a

high explosive, which results in a shock pressure wave front, while an implosion results in a radiating pressure pulse caused by the sudden energy release of a failed implodable volume under the water. The use of UNDEX and implosions at depth in the sea environment are attractive means to eliminate adversarial threats and maintain control of the undersea domain. While the phenomena associated with UNDEX has been studied much more extensively as of late, especially since its devastating effects became evident during World War II, implosion effects are not yet characterized. In both cases, the pressure loading, the interactions between a delivery device and the seabed target, and the resulting damage effects require further study so as to determine the most appropriate choice of initiator in a particular sub-sea setting.

Complicating this matter is the fact that seabed depths vary from the shallow waters of the surf zone all the way down to the abyss, and even trenches that pass 10,000 meters in depth. Additionally, during such an operation, the delivery vehicle and other resources need to be preserved. This is contrary to the typical implementation of both UNDEX and implosion events which radiate outward, providing an overpressure more or less uniformly in the horizontal plane, with some differences in the vertical direction due to the effects of hydrostatic pressure. Previous implosion research modeling and simulation has primarily focused on geometric properties of implodable volumes such as cylinders and spheres, and the resulting pressure yield. Preliminary studies using 1D fluid models indicated a potential for implosion-initiated peak pressures to far exceed those of UNDEX. However, the subsequent pressure loading and duration were also predicted to be lesser than that of the UNDEX equivalent. Translating these basic loading phenomena into damage mechanisms in order to defeat the target has yet to be considered. This current work expands on previous research by comparing high explosive source pressure yields derived from UNDEX to implosion-initiated pressure loading of air cavities and collapsible thin-walled volumes of various geometries across the design space.

Findings and Conclusions

Physics based modeling and simulation supplemented by the analyses of previous studies indicates that there is potential in the implosion-initiated defeat of seabed targets. A design space survey of pressure loading both by initiator size (volume) and detonation depth was performed using the Dynamic System Mechanics Advanced Simulation hydrocode. Peak pressure response at a distance of 10 charge radii from the source was used to compare the simulated explosion and implosion cases in 2D and 3D fluid domains. Pressure results were tabulated by depth, initiator type and other selectable parameters such as radius, length to diameter ratio, thickness and material properties.

Conventional underwater explosives are self-contained pressure release devices, bringing together both the initiation and chemical components required for detonation and subsequent combustion. They are relatively dense as compared to implodable devices, and thus less susceptible to variance in depth. These simulations produced results as expected: their pressure yield was found to be in accordance with recognized formulae derived from empirically collected data. On the contrary, implodable volumes, which are less compact, require fine tuning of their structural casing based on the expected depth of operation, and are more difficult to accurately predict. The cylindrical geometry was found to be superior in producing overpressure when compared to the spherical geometry, and depth was found to be a factor in the magnitude of pressure captured in the simulation time histories.

Both types of initiators bring their own safety concerns. While high explosives are more routinely used,

they still pose undesirable characteristics such as high sensitivity, volatility, hygroscopicity, and toxicity. Implosion events on the other hand, suffer from the unpredictability of the process itself. Though not a direct focus of this study, practical engineering issues such as size, weight, and fabrication of the initiators, transportation and handling, and their deployment, exist in the case of implosion initiation devices. The details of these features are important in accurately capturing the method of failure initiation (crack, spark, etc.) in the implodable volume casing, which varies and presents potential challenges in modeling the result within the finite element method code and the physical article as well.

The study conducted here continues to build upon the knowledge of implosion, and our results should help better inform decision makers in the planning and selection of potential deep-sea initiator designs for neutralization of seabed targets.

Recommendations for Further Research

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. A related concept is one of implosion-induced water-jetting as a means of potential damage mechanisms for seabed effectors.

NPS-19-N080-A: MEMS Acoustic Sensor for UAV Detection and Localization

Researchers: Dr. Fabio Alves and Dr. Gamani Karunasiri

Student Participation: LT Todd Coursey USN and LT Austin Fleming USN

Project Summary

The proposed one-year research effort was to explore the feasibility of using microelectromechanical systems (MEMS) acoustic sensors to detect and localize unmanned aerial vehicles (UAVs). The detection and localization schemes are based on the hearing organ of the parasitic fly *Ormia ochracea*, which performs a signature-based detection of chirping crickets. In order to do that, we studied and analyzed acoustic signatures of available UAVs to identify common spectral tones used for modeling, simulation, and theoretical evaluation of the sensors. The *Ormia*-based MEMS sensors are around 50 times smaller than the sound wavelength they detect, and the final system, including electronics, would be smaller than a square centimeter. Additionally, they can exhibit greater signal-to-noise ratio and directional response than currently available broadband microphones. Preliminary results indicate a great potential for use of this type of sensor 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

When compared with the electromagnetic counterparts, acoustic sensors have many advantages in detecting drones: non-line-of-sight, passive, low-cost, low-power, light, and small. Acoustic sensors are the primary sensors employed in most unattended ground sensor systems because they can provide

detection, direction finding, classification, tracking, and accurate cueing of other high-resolution sensors (Srour & Robertson, 1995). They are equally effective against continuous and transient sound sources. Recently, the skyrocketing small flying UAV technology has pushed the sensor field towards the characteristics that match the spectrum of sound sensors.

The motivation for this research is to localize sound sources with sensors much smaller than the wavelength they detect and without the need of complex array arrangements (Letowski & Letowski, 2012; Miles, Robert, & Hoy, 1995). One attractive way is to use MEMS sensors based on the parasitic fly *Ormia ochracea*. This parasitic fly has developed a unique approach to direction finding, and it is able to localize chirping crickets with remarkable accuracy. Miles et al. (1995) found that the two eardrums of the fly are mechanically coupled and have two natural resonant frequencies. The fly employs the coupling between the two modes to sense a sound's direction, making use of the unequal vibrational amplitudes of the two eardrums (Wade & Deutsch, 2015).

Our research group has a legacy know-how on *Ormia*-based detectors (Touse et al., 2015; Downey & Karunasiri, 2013; Wilmott, Alves, & Karunasiri, 2017). The sensors can be tuned by design to be sensitive to specific spectral features (specific tones), while filtering out all undesirable acoustic bands. Previous studies of the sensor showed high directional accuracy (less than 2 degrees for single tone and less than 4 degrees for sound bursts, such as gunfire). Preliminary studies with small flying UAVs indicate they exhibit unique spectral features that the MEMS sensors could be employed to detect. *Ormia*-based sensors can exhibit a greater signal-to-noise ratio than currently available broadband microphones, and directionality can be achieved with a single sensor. In this context, we hypothesized that MEMS sensors can be effectively used to detect and localize UAVs. The study explores a novel application for a successfully developed MEMS directional acoustic sensor by modifying its spectral response (by design) to perform signature-based detection.

Findings and Conclusions

We have selected specific sound frequencies for UAVs based on their acoustic signatures, and studied the response of customized MEMS sensors against flying targets in a controlled environment and an open field. The data was collected to assess the performance of the sensors and compare it with conventional microphones. The ability to effectively provide awareness, detection and localization of the acoustic sources on the soundscape could allow immediate countermeasures towards threats or cooperative operation with partner platforms. These capabilities, obtained by miniature sensors with minimal impact on the internal signal processing and computational resources and power budget, could signify a tremendous source of operational asymmetry.

On one hand, the conducted feasibility study of miniature acoustic directional sensors for UAV localization directly addresses the requirements specified by the sponsor: (a) low cost; (a) small form factor; (b) low power consumption; (c) greater detection range than available solutions; and (d) single sensor directionality. Such characteristics could be helpful for applications in battlefield environments, and eventually allow for employment of networked distributed sensors, in order to triangulate and track flying UAVs. On the other hand, this study allowed the expansion of the know-how of the sensor operation theory: the impact of environmental conditions such as humidity, wind gusts, dust, and background noise on the sensor performance. In addition, we gained a greater understanding on the acoustic signatures of the sources intended for detection (UAVs) and their environment of operation, allowing for more efficient future study cycles.

During the initial phase of research, Naval Postgraduate School students from the Physics and Systems Engineering departments recorded and studied acoustic signatures of several UAVs. Cross spectrum, cross correlation, and other analysis techniques were used to find the specific spectral features that tailored the MEMS sensor optimum response. This was performed across several flight regimes of a single drone and across several small flying UAVs. Next, using finite element modeling, we studied the MEMS sensor performance optimized to the perennial frequencies found during the acoustic signature analysis. The newly developed sensors were tested in an anechoic environment and on the field. Their performance compared with current acoustic detection systems. Directional response accuracy of localization was tested utilizing multiple sensors in the field. Finally, the readout and signal processing electronics were studied and optimized to provide maximum performance in detection range. Initial results indicate that our Ormia-based MEMS sensors could outperform available high-end microphones in two categories: detection range and directional accuracy.

Recommendations for Further Research

It is important to highlight that the Ormia-based acoustic sensors have been studied in the past decades; however, those results never left the research laboratories. Therefore, designing, tailoring and optimizing them for specific applications is intrinsically novel, and will require a few more cycles of studies. The future work should encompass the expansion of the single sensor capability for a network arrangement of distributed sensors that can be potentially used for 3-D localization and for tracking of the intended acoustic sources. New demodulation techniques must be investigated to improve performance as well as sensor ruggedizing for field operation.

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NPS-19-N082-B: Officer of the Deck Competency Data Collection and Analysis

Researcher: Dr. Jesse Cunha

Student Participation: LT Robert Dearth USN

Project Summary

Recent ship collisions have heightened the U.S. Navy's focus on the development and tracking of mariners' skills. Using data collected by the Surface Warfare Officer School (SWOS), we estimate the statistical relationship between officers' prior experience and their current ship-handling proficiency. Our sample contains 164 randomly-selected first-tour Officers of the Deck (OODs) who were serving on 61 ships in 2018. Officers' recent experience was self-reported in a survey, and proficiency in a ship-driving simulator exercise was assessed by a post-command commander or captain. Participation was mandatory and compliance was full, ensuring that the sample is representative of the population.

We find that mariners' skills, knowledge, and experience on the bridge are meaningfully correlated with proficiency. This finding suggests that policies designed to encourage additional opportunities for deliberate practice may mitigate short-term skill degradation and lead to long-term mastery of maritime skills. In light of our findings, we suggest policymakers increase resources for simulator training, and encourage the use of simulators to mimic myriad, complex situations that a mariner may encounter in real world operations.

Keywords: *Officer of the Deck, OOD, proficiency, experience, simulator, training*

Background

Individual level data that explains the quality and quantity of ship-handling experience amongst U.S. Navy OODs is not typically recorded until after an accident has occurred, and there has not been a systematic recording of mariners' proficiency; both elements (experience and proficiency) are necessary to understand the determinants of proficiency. A newly-developed Mariner's Skills logbook aims to fill this gap via mandatory recording of operational experience, but it is not currently being paired with contemporaneous observation of a mariner's demonstrated skills.

In 2018, SWOS conducted a pilot data collection in an effort to understand the determinants of OOD proficiency, and they asked us to perform a statistical analysis of the data and offer policy suggestions. Our research was guided by a review of the literature on both civilian and military settings, which broadly concludes that observable characteristics of operators—including fatigue, age, gender, experience, and prior operator violations—are significant predictors of operator safety (Cantor et al., 2010; Monaco & Williams, 2000). Research has also shown that safety margins are further diminished due to skill atrophy (Seltzer & McBrayer, 1971). Furthermore, the use of logbooks has been found to have a positive effect on safety, and the adoption of electronic logbooks contributed to even greater safety improvements, due to the ease of managerial oversight compared to paper logs (Cantor, Corsi, & Grimm, 2010).

Findings and Conclusions

We used a mixed-methods approach, including both a quantitative analysis of the existing data collected by SWOS and an investigation into an optimal data collection and dissemination system.

Our first task was to clean and summarize the database provided by SWOS. The data contained three parts: the self-reported survey data, the assessment of simulator performance, and scores on written assessments of a mariner's skills. The survey data identified the commissioning source, ship class, and home port; time spent in various activities, such as time spent on board the ship, the amount of time spent underway, and the number of months since qualifying as OOD; the number of underway watches served; and the number of special evolutions completed, such as anchorings or straights transits. The simulator assessment data was scored on a 4-point scale, ranging from "unsatisfactory" through "exceeds standards" in five sub-categories, and on a 3-point scale for an overall assessment category ("significant concerns", "complete with concerns", "complete with no concerns"). The written assessments included percentage scores on a rules-of-the-road test (RoR) and a navigation, seamanship, and ship-handling (NSS) test.

While we found meaningful variation in most of the variables, we discovered several that should have been collected differently in order to optimally address the research questions. In particular, the experience and time-in-position data were collected categorically instead of linearly, and the simulator assessment was collected with too few categories. We discussed these deficiencies with SWOS and they have implemented our suggestions for on-going data collection efforts.

Next, we performed a statistical analysis of the 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 competency checks, and the explanatory variables (the independent variables) are the observed demographic and experience-related variables. 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 days underway in dense traffic settings. A multivariate regression model allows us to estimate partial correlations between independent variables and OOD proficiency (for example, the partial correlation of commissioning source with proficiency), which are the statistics that should be used to inform predictive models of OOD competency and optimal OOD staffing.

Our main findings from this analysis are that many of the indicators of skills, knowledge, and experiences are correlated with mariner proficiency. For example, officers who completed more special evolutions, those with more days of experience on the deck, and those who passed the RoR and NSS tests received statistically significant higher scores in the simulator exercise. Currency of skills, such as the time since attending a Bridge Resources Management course, were not significant determinants of proficiency; however, we note that there was limited information on an officer's currency, and we suggest collecting more granular data in the future to explore how skills degradate over time.

Recommendations for Further Research

Our findings of meaningful statistical correlations between measures of experience and proficiency suggests that the Navy may be able to adjust its training policies to improve ship-handling. However, more detailed data must be collected on both experience and proficiency as described above if we intend to make specific suggestions for policy.

The Navy should continue to collect high-quality, detailed data, and continue to ensure that any data collected is representative of the population, while also putting into place a system of continuous evaluation which can inform real-time changes in training polices.

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NPS-19-N125-B: Operational Internal Wave Prediction Validation and Impacts

Researcher: Dr. D. Benjamin Reeder

Student Participation: No students participated in this research project.

Project Summary

Anti-submarine warfare (ASW) in the South China Sea (SCS) is very challenging, particularly in the presence of large, episodic, nonlinear, and nonlinear internal waves (NLIWs). Oceanographic research at the Naval Postgraduate School has demonstrated that these NLIWs cause operational hazards and acoustic field anomalies. Operational ocean models may be capable of predicting the occurrence of these NLIWs, but must be validated against in situ data. This work consisted of a major field experiment in the SCS, analysis of data from this experiment in 2019, and another in 2005-2006, along with a comparison of the collected data to model predictions. These results confirm the capability of operational ocean models to predict the presence of NLIWs in the SCS.

Keywords: *South China Sea, internal waves*

Background

The SCS is a large, semi-enclosed, tropical, marginal sea with a deep basin in the northeast and an expansive shallow-water region to the west and south. It is unique for at least two reasons: its growing geo-political significance and its exceptional oceanographic features, which impact submarine operations and acoustic ASW. The SCS is host to the world's largest observed oceanic NLIWs. These very large NLIWs are generated in the Luzon Strait twice per day during most lunar cycles, have amplitudes typically exceeding 400 ft., and create very large perturbations to the water column sound speed profile as they propagate westward to the continental shelf. These internal waves have been studied via oceanographic field programs and physical modeling to investigate their generation mechanism, propagation speed and structural evolution, energy transport and dissipation, and environmental impact (Simmons et al., 2011; Jackson et al., 2012; Alford et al., 2015).

Research into the acoustic propagation characteristics of the SCS began with the Asian Seas International Acoustics Experiment (ASIAEX) in 2001, funded primarily by Taiwan's National Science Council and the US Office of Naval Research, and originally focused on the shelf/slope front in the northeastern SCS. During the field experiment, what are now known to be the world's largest observed high frequency NLIWs were discovered (Ramp & Tang, 2001).

Since ASIAEX, a number of other research programs followed, including WISE/VANS, NLIWI/SCOPE, QPE, IWISE, and ITOP. The NLIWs have been observed to scatter acoustic energy from a deep source below the thermocline to depths throughout the water column, due to its large perturbation of the depth-dependent sound speed field (Chiu et al., 2004). The ambient noise field in the deep basin has been correlated to the seasonal variation of the SCS environment over a period of one year (Chiu et al., 2012). Trains of high-frequency elevation waves are produced on the continental shelf by the shoaling trans-basin NLIWs; these elevation waves draw relatively cooler water up from the seabed and create acoustics ducts, which generate 10 dB anomalies in the acoustic field along propagation paths nearly parallel to the wave fronts (Duda et al., 2011). The focus of this work is the validation of the operational ocean model's capability to predict the occurrence of these NLIWs.

Findings and Conclusions

This effort consisted of three parts: (a) planning, preparation and execution of a major international field experiment in the SCS with Taiwanese colleagues; (b) analysis of the collected data, and (c) comparison of data to model predictions. Three environmental moorings were deployed along a line to the east of Dongsha Atoll in water depths of 100, 300 and 500 m. The instruments on the environmental moorings monitored temperature, salinity, pressure and current velocity. Additional instruments were deployed on the seabed in water depths of 1000 and 2000 m, farther to the east. The moorings were deployed on May 15, 2019, and recovered on June 23, 2019. From this very large dataset, the present effort focused on temperature data collected at the 500 m mooring, in order to compare the observed temperature at 125 m depth to predicted temperature at 125 m depth. Data extraction, plotting and analysis showed that during the 39-day observation period, more than 70 large NLIWs passed the mooring. Data from this field experiment in 2019, as well as another field experiment in 2005-2006, were then compared to predicted temperature. While the predictions underrepresent the NLIWs due to insufficient spatial and temporal resolution, they contain structure in the predicted temperature that is correlated to observed temperature fluctuations. These results confirm the capability of operational ocean models to predict the presence of NLIWs in the SCS.

Recommendations for Further Research

The present study is limited to two data sets; due to naturally occurring variability in the SCS's oceanographic environment over multiple time and spatial scales, additional data collection efforts and model/data comparisons are required. These future efforts will contribute to a more robust and reliable prediction.

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NPS-19-N156-A: Surface Warfare Proficiency Knowledge Management Architecture

Researchers: Dr. Mark Nissen and Dr. Shelley Gallup

Student Participation: No students participated in this research project.

Project Summary

As a key tenet of readiness, it is important to know, measure, and understand unit-level proficiency and individual career proficiency. This is especially relevant in trying to assess the seamanship of surface warfare officers (SWOs). This research works to develop a knowledge management (KM) approach in order to enable real-time tracking and future forecasting of SWO proficiency. The KM approach will be developed to enhance quality design characteristics such as intuitive operation, natural data entry, agility, and global reach.

Keywords: *surface warfare, readiness, proficiency, seamanship, knowledge management*

Background

The Navy SWO Community provides a vital, sophisticated capability to address increasingly dynamic and unpredictable threats around the world. Effective performance in the SWO Community requires a somewhat unique set of skills and capabilities, which center on life and work aboard ships at sea. Such skills and capabilities are generally expected to grow in predictable ways, and the Navy enforces established qualification procedures to help ensure that its people are proficient before taking responsibility for critical jobs aboard ship.

As with any human endeavor, however, different people possess varying levels of motivation, and each person learns new skills at an individual rate. Moreover, given the persistently high tempo of surface warfare operations around the world—coupled with shortened training times for SWOs—many critical skills are learned while underway via on the job training (OJT), mentoring under instruction (UI), and personnel qualification standards (PQS). Hence, it's difficult to know exactly how proficient each individual person aboard ship will be or, by extension, how ready a ship's crew is before getting underway. Furthermore, not all ships (even of the same class) are configured or operated identically, so OJT and experience aboard one ship may not be 100% transferrable to another. As noted in the Navy's recent comprehensive review (United States Fleet Forces Command [USFFC], 2017), factors such as these can contribute to questionable seamanship, ineffective communication, and even avoidable collisions at sea.

This leads to four primary research questions: What are the key factors that contribute to individual and unit readiness? How can such key factors be measured, tracked and forecasted? What kinds of readiness knowledge and information are required for intuitive yet reliable assessment? What kind of architecture can support a KM approach to measurement?

In this study, we bring to bear the state of the art in terms of Knowledge Flow Theory (KFT)(Nissen, 2014), analysis, visualization, and measurement (Nissen, 2017, 2019) in addition to recent research on the SWO Community (Nissen & Tick, 2018). We also understand the importance of working with our project sponsor to tap the detailed and relevant insight and experience available. Hence, this effort combines some of the best thinking about knowledge dynamics and measurement with that of surface warfare proficiency and readiness, to create an integrated, practical, SWO-focused endeavor.

Findings and Conclusions

The research questions are pursued through the following major project tasks:

- Task 1: Research the academic, doctrinal and professional literatures to understand the key factors that contribute to individual and unit readiness.
- Task 2: Understand how such key factors can be measured, tracked and forecasted.
- Task 3: Build upon our understanding of knowledge and information flows to identify the readiness knowledge and information required for intuitive yet reliable assessment.

Key findings center on leveraging our knowledge visualization and measurement techniques to depict and quantify the dynamics of SWO knowledge aboard ship. For illustration, we excerpt a critical situation from the Navy's comprehensive review leading to the fatal collision aboard the McCain, which we analyze, diagram, and measure. We elucidate important, novel insights into the manner in which knowledge flows—and fails to flow—during maneuvers for which exacting seamanship and teamwork are required, and we both delineate and quantify the huge knowledge loss that can result from watch team changes at sea. We also offer recommendations for mitigating such knowledge loss.

We report how it is critically important to expand Navy consideration of SWO proficiency beyond the individual level: teams of people (e.g., watchstanders on the bridge) must be able to work proficiently together. Hence, it is insufficient to track and assess the knowledge of individual SWOs aboard ship.

Key findings also center on leveraging knowledge, information, and processes associated with the Aviation and Submariner Communities. Dynamic knowledge analysis demonstrated through this research represents a novel capability for the SWO Community, elucidating keen and novel insights into the associated issues and processes that cannot be understood otherwise.

Recommendations for Further Research

We recommend future work with experienced SWO personnel to create the KM architecture noted above. We have many suggestions for approaching this future research, as there is much to be done now with the problems we've identified here but have yet to solve. On the bridge and elsewhere aboard ship, team knowledge and team performance are critical: It is insufficient for each individual officer and crew member to be knowledgeable, experienced and proficient. Rather, people must perform well on teams (e.g., watchstanders on the bridge), and to do so, they must practice together; therefore, team performance is important to track. This suggests that information about the watch bill—and watch performance—for instance, may prove useful, but much work is required to outline an effective and consistent approach.

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NPS-19-N333-A: Provisioning of a Multi-int Fusion Environment in the Era of AI and Machine Learning / NPS-19-M103-A: The Running Estimate (RE) for the MEF Command Element

Researcher: Mr. Arkady Godin

Student Participation: No students participated in this research project.

Project Summary

The research integrates two previously discrete projects.

See: [NPS-19-M103-A: The Running Estimate \(RE\) for the MEF Command Element \(page 195\)](#).

NPS-19-N335-A: Improve the Effectiveness of the Decision-Maker Orientation Processes in Making Sense of the Events & Phenomena Presented by the Battlespace

Researchers: Mr. Arkady Godin and Dr. Tom Murphree

Student Participation: No students participated in this research project.

Project Summary

Planning, conducting, and assessing national security operations involves understanding and predicting the activities of adversaries and other subjects of interest. Many of these activities are strongly impacted by environmental conditions—for example, atmospheric temperature, winds, and precipitation, ocean waves and currents, and seasonal and anomalous variations in these conditions. We assessed the potential to identify predictive relationships between environmental conditions and the activities of subjects of interest, and used those relationships to produce forecasts of the activities. Our assessment used: (a) environmental data from atmospheric and oceanic reanalysis, (b) maritime vessel activity data from the Automatic Information System (AIS), and (c) aircraft activity data from the Automatic Dependent Surveillance-Broadcast (ADS-B) data set. The data was primarily for the western North Pacific region during 2014-2019.

This research developed and tested methods for processing the data and rapidly identifying spatial and temporal patterns, focusing on those that: (a) identify predictive relationships between environmental conditions and activities, (b) describe characteristic relationships for representing patterns of life (POL) for the vessels and aircraft, and (c) identify non-characteristic or anomalous activities. In doing so, we assessed how these relationships could be used in building models to receive forecasts of environmental conditions as inputs to the models, and produce predictions of vessel and aircraft activities as outputs from the models. These predictions, if skillful, would be useful in planning, conducting, and assessing a wide range of security operations. A major goal of our study was to develop and test potential methods for improving battlespace decision-making—in particular, the observation and orientation phases of the observe, orient, decide, and act (OODA) decision cycle or loop. The data is well suited for POL and predictive analyses, but there are several significant challenges in working with the activity data and related metadata. These include difficulties in: (a) availability and cost for sufficient unclassified data, (b) storing and processing the very large data sets that are needed, and (c) putting the data into formats that facilitate rapid real-time analyses.

Keywords: *aircraft activity, Automatic Dependent Surveillance-Broadcast, ADS-B, Automatic Information System.*

Background

Environmental impacts can significantly complicate the understanding and prediction of activities of interest. However, in using the knowledge of how these activities are affected by the conditions, we can more successfully predict the activities. As an example, pirate activity conducted from small boats tend to be greater when ocean surface wind speeds and waves are low, and vice versa (Cook & Garrett, 2013). Thus, accurate forecasts of ocean surface wind speeds and waves in areas where pirates tend to operate could be useful in predicting when and where pirate activity will be high or low (Slootmaker, 2011).

The same concept applies to many other types of activity, such as movements of ground vehicles, ships, and airplanes, and the launching of missiles and rockets (Hinz, 2004).

We applied this concept in an investigation of the potential to use a combination of atmospheric, oceanic, AIS, and ADS-B data to: (a) identify relationships between environmental conditions and vessel and aircraft activity, (b) characterize typical POL, (c) identify anomalous activity, and (d) use forecasts of environmental conditions to predict activities.

Findings and Conclusions

Our results indicate that environmental data combined with activity data can be useful in analyzing and predicting activities of maritime vessels and aircraft. Activity features that are especially sensitive to environmental conditions, for example, vessel and aircraft routes and speeds, time in port or on the ground, aircraft altitudes, show the most robust relation to environmental conditions. Thus, the environmental impacts for these activity features are relatively large—that is, they have a high signal to noise ratio. This means that these features are the features most likely to be accurately modeled in terms of environmental conditions, and accurately forecasted using forecasts of the conditions. Additionally, the times and locations in which these activity models and forecasts are most likely to be successful are those in which there are large and relatively predictable variations in the environmental conditions: for example, regions with large seasonal or anomalous variations, such as East Asia and the western North Pacific (Bridgman & Oliver, 2006).

In the course of the work, we found that sources of extensive unclassified AIS and ADS-B data are very limited. The main limitations are: (a) short periods and/or small regions for which data was available, and (b) the high cost of data: on the order of \$10k for a year of regional data and \$100k for a year of global data. This is in contrast to environmental data, as many sources of multi-decadal global data are readily available for free download. To identify robust and significant patterns and relationships, we used large amounts of environmental and activity data. This presented a number of data management and processing challenges, due to the large size of the data sets. Also, the three data sets came in different formats; in particular, the environmental data was spatially and temporally gridded, while the activity data was not. This was resolved by putting the activity data into the same gridded format as the environmental data. Additionally, the AIS metadata (for example, vessel characteristic data) needed to be merged with the activity data to facilitate data analyses (for example, analyses by vessel type or flag).

Recommendations for Further Research

We recommend that further research be done to: (a) identify predictive environment-activity relationships, (b) build predictive models based on those relationships, and (c) use environmental condition forecasts to force those models and produce activity predictions, in both hindcast and forecast modes. Additionally, work should be done to identify a more extensive and affordable sources of activity data, and also develop a community of research and applications specialists to support increased coordination and collaboration.

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NPS-19-N347-A: Assessing Executive Leadership Development: Leaders, Leadership Teams, and Command Agility

Researchers: Ms. Winli McAnally, Ms. Ann Gallenson, Dr. Erik Jansen, and Dr. Paul Stames

Student Participation: No students participated in this research project.

Project Summary

There are large literatures of research and publications related to management succession planning, talent management, promotions, and the many issues of manpower or Human Resources, and some research focuses on high-level Navy officer development. However, there is little or no systematic research that focuses on the needs and lived experiences of those who go through flag-level command transitions. Our research is designed to identify factors that facilitate or impede the mission alignment and effectiveness in the command transition processes; its final goal is a normative model for flag-level command transitions. Transitional issues addressed in the O-6 to O-7 (i.e. Navy captain to one-star admiral) transition, challenges of managing civilians, and political context (e.g., D.C.). Three approaches to defining effectiveness—in terms of transition goals, internal command transition processes, and stakeholders of the transition—are discussed. In Phase 1, reported here, we use content analysis of interviews with eight admirals, three senior level command members, and two Senior Executive Service (SES) members in order to identify success factors associated with the incoming commander, the command, and their institutional context and environment.

The current suggestive findings show the following at the commander's level: cautions against rapid, less-reflective, action-oriented styles, especially in more complex or political contexts (e.g., D.C.) and the importance of empowering (and giving trust) assessing risk and maintaining accountability. These results show that at the command level, a culture of trust (or mistrust) may well be the dominant moderating factor. At the institutional level, crisis and pressures driven by the larger manpower system, create a context and history that commanders and teams must understand and navigate. Additionally, types of transitions (fleet-up, direct inject, and gapped transitions) reveal the importance of time and commander familiarity as pervasive factors. Phase 2 of our research will serve to validate findings and saturate a theoretical model. Phase 3 will apply the proposed theoretical model, and Phase Four refines the model for instrumentation.

Keywords: *USN Admiral, flag-level transitions, command transitions, leadership transitions, leadership development*

Background

Research regarding developing senior Navy leaders has primarily been done at a macro, policy level (Hanser, et al., 2008). In order to bridge the gap in terms of command transitions, we inductively surface and analyzed themes that emerge from interviews, in order to build a middle-range theoretical model that can guide teams, commanders, and educators to better understand and navigate facilitators and challenges of command transitions.

Emergent themes will guide engaging the intersecting literatures on leadership and group dynamics in organizations (e.g., theories of empowerment, reputational effectiveness, and initial trust formation) that have implications and promise for understanding and action.

For example, phase one of our research suggests the following conjunctions of constructs are promising for such a model:

- The commander's development and communication of vision as it relates to individual empowerment through a sense of purpose.
- The commander's speed of action, assessment of talent and risks, and delegation patterns directly affect a culture of trust.
- The challenges posed by learning the positional aspects of being an admiral (a new one star) or moving to higher level, in more strategically-oriented executive ranks.
- The challenges of managing and leading a civilian workforce, especially in more complex or political contexts (e.g., the interagency, combined, or domestic policy level contexts).

Findings and Conclusions

We conducted 13 elite interviews, 50 to 75 minutes in length, of 8 flag officers (admirals) ranging from O-7 through O-10, 3 flag staff members (i.e., 2 captains and one commander), and 2 SES members in shore commands. The interview questions were broad, and elicited interviewees' experiences focusing on previous Navy flag-level command transitions and their perception of the factors that made them more or less successful. Transcripts were prepared, and two coders collaborated to code and analyze the data, looking for the most frequent themes as well as conjunctions or correlations of constructs. At this stage of the research, we included infrequent themes that appeared important, insightful, and worth following up on in future research (e.g., diversity and inclusion, and which upward transitions in career rank provided the greatest value for the development of commanders). Preliminary findings were organized by levels of analysis.

Findings at the level of the institution that form the context of the command include:

- The important differences in the three types of transitions, which are fleet-up (generally regarded as best for facilitating familiarity), direct inject, and gapped transitions (generally regarded as the most difficult).
- How levels of thinking and command—tactical, operational and strategic—explicitly and implicitly permeate those of interviewees (e.g., strategic levels are associated more with diverse stakeholders and more reflective, less action-oriented leadership styles).

- The importance of understanding the command's history and how immediate conditions, particularly crises, are impacting the command and its reputation.

Findings related to the command team and developing the team include:

- The centrality of a culture of trust and team confidence as indicators of the effectiveness of transitions.
- The degree to which mistrust among divisions and people can come to dominate the commander's thinking and communication challenges.

Findings related to the commander include:

- The importance of communicating an informed vision for alignment and empowerment.
- The challenges of leading and giving trust to civilians (vs. military) and how this can impact productivity and morale.
- The importance of balancing and managing trust, accountability, and risk assessments.

In addition, we discuss three approaches for effectiveness of transition: a goal-based approach (setting and accomplishing goals, sometimes mentioned with respect to vision), an internal process approach (e.g., trust and morale), and a stakeholders' approach, which is more characteristic of complex, political, and higher-level commands.

This research is qualitative, and seeks insights that can surface factors for generating a theoretical model. Further research is planned to validate the findings and construct a theoretical model.

Recommendations for Further Research

This phase of the research provides a proof of concept for design and findings, and future research is suggested to “unpack” and dig deeper into relationships like those between a culture of trust, empowerment of individuals, cognitive style of commanders, and risk assessment in the context of delegation. As the force field interpretations become more clearly understood, and as more specificity is added about them, they will become more useful for commanders and commands in creating more effective transitions. These can then be used by those who provide support in the form of formal training and education, command workshops, and coaching and mentoring.

In addition to the contributions to practice, there are possibilities for contributions to more general scholarship: for example, the literature on “initial trust formation” and on “reputational effectiveness” could be brought together. This study already suggests that key factors come together in ways that have not been studied in terms of transitioning into leadership positions. For instance, how do the intricacies of effective delegation, risk assessment, empowerment and the development of trust actually relate in the perceptions of people, and can this be operationalized and measured? How do people form judgments of reputational effectiveness? Qualitative research on command transitions in the Navy, including interview studies such as this one, and case studies of specific transitions told from multiple points of view, have the potential to address a wide range of questions.

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HQMC INSTALLATIONS AND LOGISTICS (I&L)

NPS-18-M151-A: Improving USMC Ground Maintenance through Vehicle Sensors and Analytics

Researchers: Dr. Gurminder Singh, Mr. Arijit Das, and Mr. Charles Prince

Student Participation: LtCol Dan Bartos USMC, and Capt Michael Whitaker USMC

Project Summary

Currently, all data within the Global Combat Support System-Marine Corps (GCSS-MC) is generally input via either interfaces with other systems or user manual manipulation. Adding or modifying system interfaces can be resource intensive, and simple data input is not optimal use of manpower. Vehicle-based sensors may be used to automate processes for predictive and preventive maintenance to reduce cost, increase availability and reduce risk to personnel and property. We plan to develop a system architecture to establish network linkage between Marine Corps ground vehicles and the GCSS-MC system to automate GCSS-MC service requests in support of predictive and preventive maintenance.

Keywords: *Predictive maintenance, information systems, vehicle sensor data, Internet of Things (IoT), sensors, analytics, GCSS-MC*

Background

The Global Combat Support System – Marine Corps/Logistics Chain Management (GCSS-MC/LCM) is the key logistics chain enabler for the Marine Corps. Increment 1 of the System was fielded to the Marine Corps Operating Forces in 2010 through 2012, with the purpose of providing forward-deployed logistics support with capability to "reach back" to sustainment chains as described by Headquarters, Marine Corps (2018). Additionally, the focus of GCSS-MC Increment 1 was support for supply and maintenance business processes. GCSS-MC was implemented as a commercial off the shelf (COTS) enterprise resource planning system utilizing the Oracle e-Business Suite (EBS). GCSS-MC is a web-enabled system utilizing a CONUS-based Enterprise site housing supporting databases and security infrastructure with system users connecting to the Enterprise site to update and receive logistics data. As explained by the Department of the Navy, the system architecture "centralizes logistics information for access by multiple authorized users" and achieved full deployment in December 2015 (United States Marine Corps [USMC], 2016a).

Currently, all logistics data within GCSS-MC is generally input either through interfaces with other data systems or user manual entry. This manual entry is inefficient and not an optimal use of human resources. However, existing processes to automatically extract data from interfacing systems can be exploited to minimize the burden on human users, and improve the fidelity of data triggering maintenance actions or being analyzed to support equipment decisions.

Marine Corps Headquarters has identified the need to network and monitor logistics data in addition to the problems associated with manual data entry and update within GCSS-MC/LCM (USMC, 2016a). In 2016, the Deputy Commandant for Installations and Logistics published the Marine Corps Hybrid Logistics concept. He stated that:

Success in this hybrid area will also require efficiency and sustainability in austere environments. Rolling stock and generators could be networked and monitored to increase their fuel-efficiency and use. Additionally, we must modernize our supply and maintenance capabilities. A critical element of this is bringing (GCSS-MC) to its full fielding potential (Dana, 2016).

Application of a low-cost, COTS networked single-board computer to automate GCSS-MC data input and update was explored in an effort to both support the Hybrid Logistics concept, and gain efficiencies with GCSS-MC. This exploration developed a proposed architecture to automate equipment data input into GCSS-MC or other Enterprise applications from Marine Corps equipment containing integrated data networks. Specific data examined was associated with equipment condition in order to provide the automated impetus for condition-based maintenance. In an effort to minimize changes to existing GCSS-MC code within the Oracle EBS, the COTS computer exploited existing processes and architecture already in place, and utilized by GCSS-MC to provide automated updates. The computer extracted raw data from the equipment, processed it as necessary, and then transmitted the resultant processed data to the GCSS-MC Secure File Gateway (SFG) for follow-on processing by the system.

This project focused on automation through a networked computer applied to a military medium motor transport equipment and equipped with the Society of Automotive Engineers J1939 Controller Area Network (CAN)-bus with standard 9-pin Deutsch cable connection. The automated processes monitored equipment parameters and upon achieving a specific condition, that data was wirelessly transmitted to a remote file server. Basic network connectivity was established via unclassified Wi-Fi network, with wireless capability either built into or applied to the single board computer.

The single-board computer extracted, processed, and then transmitted simulated equipment mileage to a file server representing the SFG. This data was chosen since it relates the equipment condition needed to potentially trigger a condition-based maintenance event, as well as a required data element necessary for entry into the enterprise logistics system (USMC, 2016b).

Findings and Conclusions

Using relatively inexpensive COTS hardware and open-source software, vehicle diagnostic data can be collected from existing equipment. However, this data collection and hence its analysis is limited by the capabilities of the equipment CAN or data bus network. In the case of the Medium Tactical Vehicle Replacement in this research, the J1939 protocol was nascent and implemented in a limited capacity. As newer equipment is procured with more capable CAN-bus networks, the ability to collect and process more data will improve. The results of this research support expansion of CAN-bus capabilities wherever possible should equipment undergo service-life extension programs.

Data transmitted on the CAN-bus can be processed and analyzed by the Raspberry Pi. However, the relatively trivial processing of vehicle revolutions per minute (RPMs) integrated with the network transmission, did not stress or test the limitations of the Raspberry Pi's microprocessor capability.

As additional vehicle parameters are collected from more CAN-bus messages, additional stress on the Raspberry Pi microprocessor is expected. We believe that it would be possible to use even lower compute power hardware to perform this analysis.

Automated updates of data within GCSS-MC can be enabled through the prototyped architecture demonstrated in this research by utilizing existing processes and protocols. With availability of valid DoD Public Key Infrastructure (PKI) certificates, coupled with a wireless network capability, algorithms can be constructed that automatically transmit data to designated file servers for follow-on processing and update by GCSS-MC, providing non-repudiation of the data being transmitted. This data transmission is contingent on the availability of appropriate network, software, and hardware configurations that facilitate PKI-enabled Secure File Transfer Protocol data transfer.

This work was extended to exploit the real-time logistic data collected from military vehicles and other equipment to enable predictive maintenance, making it possible to apply data-driven decision making to new realms of logistic methods. From monitoring machines on the factory floor to tracking the progress of ships at sea, predictive maintenance can enable organizations to maximize performance from their physical assets, and revolutionize traditional logistic strategies and supply paradigms.

Recommendations for Further Research

1. **Additional Vehicle Diagnostic Data Elements:** To examine the potential architecture to update logistics data, a relatively trivial data element, vehicle RPMs, was examined to simulate vehicle mileage. The J1587 and J1939 protocols accommodate many other diagnostic and condition data elements. These other data elements should be included in future architecture development to ensure viable processing and transmission of the data.

2. **Implementation of Mesh Networks:** It is very common for vehicles and other equipment to operate in groups. For example, military vehicles are often employed in convoys and military generators are often employed in pairs. In the prototype architecture explored in this research, a single vehicle was utilized. However, there can be significant benefits gained from inter-equipment communication of conditional diagnostic data. This communication could be achieved through establishment of a local mesh network between vehicles or equipment. Open-source mesh network software, such as the Better Approach to Mobile Ad-Hoc Networking, is available for experimentation and implementation. Application of a mesh network has several beneficial applications: first, if network connectivity to the file server is inaccessible to one vehicle, but another vehicle on the mesh network has connectivity, the diagnostic data updates can be achieved via the mesh network; Second, if there are unique local conditions affecting the operational condition of the equipment, those conditions can be verified by the equipment at the local level, and a single signal can be transmitted to a larger enterprise controlling node rather than each individual item transmits its own condition; lastly, if collected diagnostic data requires localized processing, inter-node communication can facilitate parallel data processing to improve efficiency.

3. **Integration with Tactical Communication Systems:** For purposes of this research, a commercial internet service in conjunction with 802.11 Wi-Fi was used to transmit the diagnostic data from the vehicle to examine the prototyped architecture. In reality, this infrastructure is not available nor realistic in a distributed, expeditionary environment.

Tactical vehicles and often configured with tactical communications systems, such as satellite or high frequency communications, to facilitate command and control of forces. Future exploration should be conducted concerning the transmission of vehicle diagnostic data across these tactical communication channels.

4. Cybersecurity: There are several areas of cybersecurity requiring additional research and investigation to examine the level of risk and possible solutions to mitigate that risk. Since the current enterprise network architecture of the Marine Corps does not include vehicles and the electronic control units (ECU) nodes of their CAN/data buses, the addition of these nodes to the enterprise network could create unanticipated disturbances. A faulty or malicious ECU could create a denial of service across a larger network. Additionally, other than the controls implemented by the J1939 and J1708/J1587 protocols, there are few protections against faulty data being transmitted by the nodes on those networks. The local or networked computing resources could implement oversight on the data produced by the nodes to identify erroneous or malicious data being produced and transmitted across the bus before it has more significant impacts on resources. Additionally, the PKI certificates used to enable the secure file transfer of the conditional data were loaded to the networked computer on the vehicle. Rather than place static PKI certificates on the computer, the certificate associated with a vehicle driver's or mechanic's common access card could be used at the time of vehicle operation to enable the secure file transfer.

5. Further Integration with GCSS-MC: The architecture explored in this research ends with the transmission of the data file containing equipment condition data to the designated gateway file server. To process the enterprise data updates, additional interface actions are required to enable the appropriate database updates as implemented with the current GCSS-MC system interfaces. These additional interface actions should be explored, including an analysis of a potential level of effort.

6. Ruggedization: The Raspberry Pi single board computer used in this research was not ruggedized to meet any military standard specifications. Reliability of the device in austere, expeditionary conditions, such as desert and arctic environments, is uncertain. Further research should be conducted to analyze the device reliability and any needed physical ruggedization needed to improve that reliability.

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NPS-19-M093-A: Cost and Operational Evaluations of Centralized vs. Distributed Class IX Inventories

Researchers: Dr. Michael Atkinson and Dr. Moshe Kress

Student Participation: LCDR Peter Rivera USN

Project Summary

The United States Marine Corps (USMC) faces the critical issue of setting its inventory policies to meet the Class IX repair-parts demands put on its Divisional Supply Management Units (SMUs). Specifically, the USMC seeks to improve its logistics operations for repair parts at the SMUs. USMC Installations and Logistics has partnered with the Defense Logistics Agency (DLA) to investigate whether increased collaboration with DLA could make the SMUs more efficient and effective.

Efficiency is measured by reduced inventory at the (SMU), and effectiveness is measured by reduced customer wait time. The goal in this research is to find the best efficiency-effectiveness tradeoff, which is determined by the balance between distributed inventory at the SMUs and concentrated inventory at the DLA. Based on time-phased demand data collected at the SMU of the (MEF I), we developed a simulation mimicking the requisition-supply cycle. Our simulation, implemented on six repair parts, facilitates an analysis of the distribution-concentration balance regarding these items. The analysis produces plots visualizing efficiency-effectiveness tradeoffs, which can help decision-makers choose the right distribution-concentration balance. We comment about the results of the simulation and offer some recommendations regarding inventory policies. For some of the analyzed repair parts, we show that the MEF I SMU can reduce the inventory levels of several parts by relying on DLA support, while maintaining adequate customer wait time.

Keywords: *logistics, inventory, customer wait time, centralized vs. distributed*

Background

Operating under an efficient and effective inventory policy is important for the USMC, as shortages of critically needed parts at certain locations and times could mean the difference between mission success and mission failure. By setting an optimal inventory policy, decreased inventory costs and customer wait times would positively affect mission performance and cost. The status quo, however, could force the USMC and, more importantly, the warfighter, to operate with a less than optimal system. By supporting the various requirements from MEF customers, the SMUs play a key role in supporting the Marine Corps warfighter.

The DLA is the SMUs main wholesale source of repair-parts, and a reorder policy by the SMU is determined by two main parameters: reorder point (RO) and reorder up-to point (ROP). RO is the threshold level of inventory in the SMU that triggers a reorder; ROP is the “up-to-level” of a reorder. That is, a reorder size = ROP – current inventory.

The values of a (RO, ROP) pair may well be the critical point between a shortage of an item, and unused surplus, however, historically, SMU forecasting miscalculations have periodically caused parts to be ordered at the incorrect time and/or in the incorrect amount.

These inaccuracies have led to various problems, including increased inventory costs and shortages of critically required parts. Moreover, customer wait times (CWT), the time from when the part is first ordered to final receipt by the customer, were adversely affected by this type of incorrect demand forecasting. Establishing a correct inventory policy is critical. Therefore, in seeking a possible solution, USMC and the DLA have embarked on a series of trials to examine if increasing USMC-DLA logistics integration can provide it. The results of these trials were inconclusive, which triggered our research – seeking an analytic solution for the question of effective and efficient inventory policy at the SMUs.

Findings and Conclusions

This research develops modeling and simulation tools to analyze the USMC logistics system from the SMU perspective and its interaction with the regional DLA supply depots. In addition to developing a tailored simulation for the resupply cycle, the research examines the advantages and disadvantages of possible modifications of the current system, such as enhanced decentralization or greater collaboration with DLA, which leads to centralization. Inventory management policies such as reorder frequency and amount are also examined. Details are as follows:

The USMC resupply cycle comprises five main stages:

- **Identifying** shortage in the inventory of an item,
- **Generating** a requisition by a customer or SMU,
- **Processing** a requisition by routing it in a specified order to a potential supplier,
- **Handling** the requisition at the supplier, a stage that may take from few hours to a few days,
- **Shipping** the supply and receiving it by the customer or SMU.

Note that there are two main resupply cycles: one that is initiated by and terminated at the customer (a USMC tactical unit), and another that is initiated by and terminated at the SMU when the inventory level of an item reaches its RO.

Our simulation follows the five stages described above, and the demand frequency and size are simulated based on real demand data collected from the SMU of MEF I. In addition to the RO and ROP described in the Background section, we also analyzed a third parameter—frequency of inspection (FoI). This parameter determines how often the inventory level of an item is inspected as excessive inspections may lead to unnecessary requisitions, while sparsely scheduled inspections may lead to undetected and severe shortages.

The simulation is implemented on the data of four reparable stock items that vary in the frequency and size of requisitions. The analysis examines the tradeoff between the ROP and CWT. ROP is a proxy for the cost of inventory – higher ROP implies larger inventories that occupy storage space and lock in purchase funds. CWT is a measure of service quality: how long needs a customer to wait to receive its order. This tradeoff is analyzed while varying the FoI, which is a proxy for a control parameter, and the value of the RO, as a percentage from the ROP.

Comparing the results of the analyses with current practices at the SMU of MEF I, we conclude that for certain items the ROP could be reduced, thus saving inventory costs, while maintaining acceptable CWT. We also recommend, for some items, new RO values and specify efficient FoIs. Specifically, for items that have a moderate level of demand that an ROP of two months of demand, we find that a RO equal to 20% of ROP, and an FoI of two weeks strikes a reasonable balance between CWT and inventory cost.

Recommendations for Further Research

The model developed in this research assumes vertical flow of supplies where repair parts move along the hierarchy: DLA to SMU to customer. While still more of an exception than a rule, lateral flow between SMUs are possible, and perhaps even desirable. As this flow is not captured in our model it could be part of a model extension. A second model extension would be to expand the scope of the model to include third SMU (MEF III), other forward deployed logistic units at the operational level, as well as modeling in detail the DLA operations with all its relevant installations. Finally, the current model touches on budgetary considerations only thorough the ROP proxy. Further research would involve estimations of inventory, handling and shipping cost so that the tradeoff between effectiveness (CWT) and efficiency (cost) will be more realistic.

NPS-19-M283-A: Impacts of Hot Isostatic Pressing 3D Printed Parts

Researchers: Dr. Claudia Luhrs and Mr. Troy Ansell

Student Participation: LT Joshua Ricks USN and LT Chantel Lavender USN

Project Summary

The use of additive manufacturing (AM) techniques, also referred as three-dimensional (3D) printing, and used to generate objects layer by layer, presents multiple advantages over technologies that rely on machining or removing sections of a larger piece. AM methods can produce complex parts without waste of raw materials, and promise to greatly reduce costs and increase efficiency in our supply chain. In addition, polymeric materials can be directly 3D printed and immediately used. In contrast, metals and alloy components require post-processing operations, such as thermal treatments and hot isostatic pressing, in order to obtain the desired properties. Without the proper treatments, the 3D-printed metal parts will be unreliable and pose risks to the systems that will integrate them.

The goal of this study was to conduct materials characterization of 3D-printed maraging steel specimens after each processing step, in order to identify which post-printing conditions should be employed to produce parts with the mechanical properties that could meet the sponsor's objectives and/or operational needs. For this effort, Naval Postgraduate School (NPS) faculty and students worked with Albany's Marine Corps Logistics base personnel.

Overall, the study identified which printing direction, heat, and surface treatments, render parts with the highest hardness, yield, and ultimate strength. To maximize these characteristics, we provide recommendations regarding the employment of optimal parameters during printing.

Keywords: *additive manufacturing, AM, metal/alloy AM, three-dimensional, 3D, 3D metal printing, maraging steel, post-processing*

Background

Metal and alloy 3D printing techniques physically join the materials layer upon layer to render tridimensional objects. Some of the common technologies available for metal AM include directed energy deposition (DED) and powder bed fusion (PBF) methods, although others are under development. In DED, melted material is directly deposited onto the part undergoing printing using a raised nozzle.

In PBF, a roller or spreader distributes powder in a platform and a heat source is directed to the sections to be joined. Independent of the method, after AM fabrication, a few post-processing steps are required to render an object with the microstructure, properties, and surface finish desired for engineering applications:

- *Residual stresses and stress relief*

As it is built layer by layer, the metal suffers heating and cooling cycles which produce internal stresses that need to be relieved to prevent warping and cracking in the final part. Heat treatments are conducted after the part is built in inert atmospheres to prevent oxidation.

- *Heat treatment*

The as-produced parts might require aging, solution annealing, and controlled cooling procedures to develop the microstructures that will fulfill the properties expected.

- *Surface treatments*

The surfaces of AM parts might also require surface finishing steps to reduce roughness and remove partially melted particles that will otherwise act as stress concentrators.

In sum, post-processing treatments are indispensable in order to produce 3D-printed metal parts which will fulfill their load bearing and lifecycle requirements.

The hypothesis of this study was: Tensile test data and microstructural analysis of 3D-printed samples heat-treated under different conditions will allow us to determine which post-printing steps are required to produce specimens that meet the sponsor operational needs.

The research questions that the study helped answer included:

- What is the impact of heat-treating 3D-printed parts on the properties of the material?
- What microstructures are present at diverse conditions?
- Will the heat-treatment operations produce changes in the local composition of the materials?
- How do the mechanical properties of the heat treated (HT) specimens compare to those of parts before treatment?
- How do the properties of 3D-printed parts compare to samples produced by subtracting methods such as computer numerical control (CNC)?
- What is the distribution of phases and properties in the samples' cross section?

Findings and Conclusions

The methods employed to characterize the mechanical properties, the microstructures, and the composition of the specimens under study, were a perfect fit to fulfill the goal of the analysis. Instruments such as the scanning electron microscope and energy dispersive spectrometer, along with hardness and tensile tests, allowed us to determine the effects that post-printing steps, such as diverse heat-treatments, had on the features and properties of parts printed in diverse directions.

Some of the key findings included:

- Samples heat-treated at 490 °C had the highest ultimate tensile strength and yield strength while parts manufactured by traditional techniques, such as CNC, and samples heat-treated at 900 °C had the lowest values.

- Specimens printed in the z and xy directions had the highest strength and closely matched the 3D printer manufacturer's benchmark values. The lowest strength was found in samples printed using a 45-degree angle. The later observation is supported by fracture mechanics calculations.
- The AP samples presented unusual fracture surfaces. This observation seemed to be related to surface imperfections and a lack of fusion. However, those features did not have a measurable impact on the yield strength, ultimate tensile strength or hardness. Susceptibility to corrosion, however, might increase due to lack of fusion found near surface.
- Sand-blasted samples had a typical fracture surface with crack initiation forming towards the middle and propagating outward. Sand-blasting samples decreased surface roughness and had an observed impact in the failure mode of AP sample. In order to reduce the number of surface imperfections that will act as stress raisers, it is recommended that samples are sand blasted after support structures are removed.

Maraging steel tensile specimens were printed at the Marine Corps Logistics Base Albany and sent to NPS for heat treatments, testing, and analysis. Mechanical properties such as yield strength, tensile strength, and hardness were determined and compared with articles produced by traditional manufacturing techniques, and with the benchmark set by the 3D printer manufacturer. The properties of as-printed (AP) and HT parts indicated that 490°C is the temperature that renders the strongest specimens when compared to those heated to 600 and 900 °C. Electron microscopy observations identified the presence of precipitates responsible for the increase in strength in HT-490. The data gathered helped identify that the printing direction (xy, z or 45-degree angle) greatly influenced the samples' properties, with 45 degrees showing the weaker parts. Additionally, for each printing condition, fractographic analyses were conducted to determine crack initiation points and failure mechanisms. The microstructural analysis identified small areas with evident of lack of fusion near the surface of most specimens. However, those features did not have a measurable impact on the yield strength, ultimate tensile strength, or hardness. Nonetheless, susceptibility to corrosion increased due to lack of fusion.

Recommendations for Further Research

Based on our results, it is recommended that immediately after thermal processing, heat treated maraging steel parts are coated or stored in conditions that will prevent the exposure of corrosive environments.

HQMC INTELLIGENCE DEPARTMENT (I)

NPS-19-M020-A: Change Detection of Marine Environments Using Machine Learning

Researchers: Dr. Mara Orescanin and Mr. Jeremy Metcalf

Student Participation: Capt Theodore Ayoub USMC and LCDR Ashley Mielke USN

Project Summary

Machine learning (ML), specifically deep learning (DL) using convolutional neural networks, is an increasingly powerful tool for classification of complex systems, including visual images and multispectral data. The focus of this study is to implement ML algorithms for 1) littoral environment classification and 2) change detection of littoral environments in order to rapidly assess changes in water quality, such as debris and oil slicks. Locally, in Monterey Bay, small unmanned aerial systems (UAS) were used to acquire data, including visual red-green-blue (RGB), RedEdge, near infrared (NIR) and infrared (IR). In doing so, these systems trained a deep neural network to recognize littoral environments on land, such as beach, marsh, and rocks, as well as water bottom type, such as sand, rock, and vegetation/algae. This database of images collected from UAS and small aircraft was used to assess coastal areas near ephemeral rivers that are known to seasonally breach, thereby changing the littoral environment and water quality through erosion/removal of vegetation as well as sediment suspension. The remote sensing images were validated by site observations as well as morphodynamic observations of beach change, in order to quantify the aerially observed changes. The results of ML model training indicate highly accurate (>90%) detection of littoral environments, both over land and littoral waters, without any need for image segmentation. These findings suggest models for targeted areas could be developed for rapid and accurate change detection post extreme events (hurricanes/tsunamis).

Keywords: *machine learning, deep learning, littoral environments, change detection, unmanned aerial systems*

Background

Landscape classification in coastal environments is a sub-discipline of large-scale landscape or land-use classification techniques involved in many areas of geospatial information analysis. Recently, ML algorithms have been implemented with heterogeneous landscapes to provide pixel-level classification of imagery (e.g. Buscombe and Ritchie, 2018; Maggiori, et al., 2017; Salamati, et al., 2012). However, the generation of ML models that are capable of pixel classification require carefully curated images with class delineations. While this method offers decent results for test images, it is not easily transferrable to datasets that have not been hand-labeled at the pixel level, or have a wide range in field of view (or other image characteristics). In contrast to pixel-level classification, this study proposes traditional image classification for heterogeneous coastal environments, in order to provide a model that is widely applicable to global coastal environments.

Aerial imagery, collected either by UAS or small aircraft, provides high-resolution (spatial and temporal) monitoring of coastal marine areas. This data can be used to identify and classify specific marine environments and visual changes in water quality, with the goal of creating a neural net that can then be used for assessment of marine environment changes. Specifically, local California coastal areas were used as proof-of-concept to identify regions including kelp forests, sandy bottom habitats, and reef/rocky bottom habitats. This approach could be applied to remote, difficult-to-patrol marine areas, including Pacific National Monuments and missile test ranges, with the intent of providing efficient management practices. This project was a collaboration with the United States Coast Guard Research and Development Center.

The research questions are:

1. Can littoral environment and water quality and bottom type be determined by a neural network image feature extraction method?

Hypothesis 1: Provided sufficient data, deep neural networks are capable of identifying different littoral environments to high accuracy (>90%).

2. Can an algorithm be created that automates an assessment of change or damage at high-risk coastal assets?

Hypothesis 2: Using the trained neural networks from Hypothesis 1, it is possible to combine predictions from two identical regions, but at different times, into a single map indicating regions of greatest change.

Findings and Conclusions

This project was a proof-of-concept endeavor to address ML capabilities, weaknesses, and applications in landscape classification of littoral environments. The first task was to compile a nearshore coastal waters database to expand upon an existing database for sub-aerial coastal zones (beach, marsh, tidal flat, etc.) that is used for change detection of the coast. This project also included adding IR images of similar coastal classes to enhance the database. This database provided the required input data to train thirteen DL neural networks in image feature recognition using RGB imagery only. The purpose of this extensive model training was to determine which model architectures were capable of classifying littoral environments. Model accuracies were all above 90% accurate, suggesting that Hypothesis 1 is well-supported. Further assessment of varying littoral water environments would be useful to expand the existing data.

The second task was to acquire new data over littoral waters with the 5-channel (RGB, NIR, RedEdge) camera that was fitted to the principal investigator's UAS. This database spans five littoral classes (beach, coastal rocks, sandy bottom, rocky bottom, and kelp/vegetation), and a new artificial intelligence model is also being developed, via LCDR Mielke's thesis, using training from scratch, as well as transfer learning, to determine the best possible method for heterogeneous coastal classification of littoral waters using 5-band imagery.

The third task of this project was to create large-scale mapped areas of coastal assets to provide a baseline status check for vulnerable and high-impact areas. The Carmel River State Beach was used, as it is a local site known for change. After an extreme flooding event (beach breaching), the same area was surveyed to assess impact using coastal change detection through the convolutional neural network tested on the generated database, as found in Capt. Ayoub's thesis.

A longer-term goal is establishing a method to identify high-risk coastal sites based on fundamental change in environment (such as beach breaching, damage to buildings).

The overall goal of this project was to determine the feasibility and usefulness of DL methods for littoral environment classification and change detection. The first phase of conclusions suggest that model accuracies are capable of classifying littoral environments. The second phase of research is still ongoing as it is student led. The research to date is included as two ongoing theses for students set to graduate December 2019 and March 2020:

- LCDR Ash Mielke: curation of littoral database. Development of littoral classification models will be completed by 12/2019.
- Capt. Teddy Ayoub: Development of change detection algorithms using Siamese networks is ongoing, to be completed by 03/2020.

Recommendations for Further Research

Given the preliminary success of multiple DL architectures for classification, a longer-term goal is to establish an easy-to-use and automated methodology to detect change and damage to coastal high-impact assets. By creating an DL-driven assessment of coastal change, a time-efficient and consistent method will be created capable of assessing any coastal feature and performing a change detection to determine fundamental changes in environment.

Specifically, it is recommended that an expansive dataset be curated to expand upon the California dataset so that model capabilities are not region specific. This will require further testing/training of neural network architectures, but will help solidify accuracies and transferability.

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HQMC MANPOWER AND RESERVE AFFAIRS (M&RA)

NPS-19-M198-A: Retention Rates influenced by Marine Corps Pay Incentives (Continuation)

Researcher: Dr. Marigee Bacolod

Student Participation: Maj Calvin Smallwood USMC and Capt Anna Fuzy USMC

Project Summary

In today's uncertain budgetary environment of sequestration and constrained resources, the Marine Corps needs precise estimates of the relationship between compensation and retention. To most efficiently manage the active duty inventory, and ensure the Corps is continuously manned with the highest quality Marines, the Deputy Commandant for Manpower & Reserve Affairs requires a thorough understanding of how Marines respond to compensation elements.

Our research aims to provide this understanding by estimating the relationship between special pays targeted to officers and enlisted Marines in the aviation community, and those Marines' retention decisions. As a case study in force drawdown, we examined the effects of separation pay incentives as the Marine Corps reduced end strength from 202,000 in 2013 to 182,000 by 2016. To facilitate the force reduction of mid-careerists, the Corps offered Voluntary Separation Pay (VSP) and Temporary Early Retirement Authority (TERA) to officers in specific ranks, and military occupational specialties (MOS). VSP and TERA induced significant number of separations among Marine pilots and naval flight officers (NFOs) between 2013 and 2016, indicating that the incentives worked as intended. However, we also found that there may have been tradeoffs in terms of quality, as separations due to VSP were disproportionately drawn from the upper end of the Fitness Report (FITREP) distribution. That is, mid-careerist Marine pilots and NFOs with better job performance as measured by FITREPs were most likely to separate due to the pay incentives. In addition, on the enlisted side, we examined the relationships between reenlistment bonuses and retention among Aircraft maintainers, finding that certified Marines are more likely to re-enlist when eligible, and that military pay and Select Reenlistment Bonus (SRB) caps' elasticities further increase the reenlistment odds of said Marines.

Keywords: *elasticity, retention, compensation, United States Marine Corps, UCMC, aviation community, separation pay, reenlistment bonus*

Background

The literature on the economics of military manpower is fairly robust, particularly on issues of compensation. How the Marine Corps incentivizes individuals to reenlist is important when competing with equivalent civilian job market opportunities that may be more enticing than continued service. For reenlistment purposes, the Marine Corps considers a wide breadth of information regarding a Marine's performance, including proficiency and conduct marks, marksmanship, performance on physical tests, and professional military education. However, the Marine Corps still struggles with ensuring the highest quality Marines are both targeted with reenlistment bonuses and invited to reenlist.

The aviation maintenance community provides a unique opportunity to identify high-quality Marines, given that retaining aviation maintenance Marines holding collateral duty inspector (CDI), quality assurance representative (QAR), and collateral duty quality assurance representative (CDQAR) certifications is of critical importance to the success of Marine Corps' aviation. These certifications both provide a relatively more objective measure of quality than typically found in personnel data, and possessing these certifications improve the value of these Marines' outside alternatives. We leveraged this fact to determine the extent to which the Marine Corps is able to employ various reenlistment bonuses to target and retain high-quality Marines.

To achieve a drawdown from 2013 to 2016, the Marine Corps began to introduce programs in 2012; VSP and TERA were two of many force shaping tools the Marine Corps used during the drawdown. Other measures included Early Discharge Authority, Selective Early Retirement Board, and Time-in-Grade Waivers. However, VSP and TERA were the main programs with monetary incentives. Marines were told VSP and TERA would be offered to overstuffed MOSs, and the Marine Corps would only use involuntary separation means on majors and above in the officer corps as a last resort.

Marine officers eligible for VSP received a lump sum, equal to 20 percent times their annual basic pay times their years of service. For a major with 12 years of service in 2013, VSP was a taxable lump sum payment of \$194,064. Marine officers eligible for TERA received a monthly retirement payment using the standard 2.5 percent multiplier, but with a 1 percent reduction for each year of service less than 20. In this case, a Major with 16 years of service would receive a retirement annuity equal to 36 percent of his/her high three base pay ((16 X 2.5 percent) – (20 – 16) = 36 percent).

Findings and Conclusions

Our research was supported by several Naval Postgraduate School theses, including those by Captain Jessica Arellano, Major Calvin Smallwood and Captain Ana Fuzy. Arellano characterized and catalogued the evolution of USMC special pays and allowances since 2000, and identified the extent to which Marines took advantage of these special pays and allowances (2018). The thorough inventory of special pays in Arellano's thesis identified the aviation community, and special pays in that community, as an ideal case for estimating the relationship between special pays and retention rates. For example, reenlistment bonuses targeted to aircraft maintainers, and the Aviation Career Incentive Pay and Aviation Continuation Pay, varied extensively during this period. Such variation is necessary in order to estimate elasticities.

Smallwood's research found that VSP and TERA increased separations—as intended—during the drawdown, and that probit models show demographic characteristics such as gender, race, ethnicity, and marital status do not statistically change the probability of taking VSP or TERA (2019). In addition, pilots and NFOs with Marine Corps specific qualifications take VSP or TERA at statistically lower probabilities for certain years during the drawdown, suggesting the Corps did not lose those with Corps- and MOS-specific human capital investments. In terms of quality, however, VSP and TERA takers have wider Reporting Senior distributions than those that stayed or separated by other means. This suggests significant tradeoff in quality and quantity, as mid-careerists left as intended, but high-quality pilots and NFOs left at disproportionately higher rates (Smallwood, 2019).

Fuzy's study examined enlisted aviation maintenance communities and the effectiveness of enlistment bonuses, by employing multivariate regression analysis using personal and financial data (2019).

She found that aviation maintenance specific skill certified Marines are more likely to reenlist when eligible, compared to aviation maintenance Marines without a CDI, CDQAR, or QAR certification, and that military pay and SRB caps elasticities further increases reenlistment odds. Additionally, the increasing quality of a Marine decreases the odds she will re-enlist, because her human capital is more transferrable to civilian job market opportunities than a lower quality Marines'. Finally, pay and bonus cap elasticities correlate to increased reenlistment probabilities, but they are not causal.

Recommendations for Further Research

In addition to Naval aviators, the Marine Corps offered VSP and TERA to a large portion of the ground officer MOSs, as well as enlisted MOSs during the 2013-2016 drawdown. Therefore, when planning future drawdowns, it would be useful to study how different ground officers and/or enlisted MOSs were affected by separation pay incentives such as VSP and TERA, and contrast their response with the findings in this project. Blended Retirement System effects on separations also need to be considered, given that the cliff-style vesting of the 20-year retirement system is no longer a key motivating factor to keep mid-careerists in the Marine Corps, so future drawdowns may not need as high levels of VSP and TERA incentives. Lastly, given the crucial need for qualified aircraft maintainers, it would also be useful to evaluate the aviation maintenance-specific kicker bonuses used to incentivize continued service of Marines with CDI, CDQAR, or QAR certifications, made available beginning in FY2018. Separately designating these Marines into their own subcategory of MOS may allow manpower managers to better track and manage them.

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HQMC PLANS, POLICIES & OPERATIONS (PP&O)

NPS-19-M238-A: Modeling and Simulation Tool to Enhance and Explore the ROE Design Space for NLW

Researcher: Dr. Steven Hall

Student Participation: No students participated in this research project.

Project Summary

The goal of this multi-year effort is to define an analytical tool (WRENCH) that will support operational planners and ground commanders in defining contextually appropriate and effective rule-of-engagements (ROEs) for the use of non-lethal weapons against potentially hostile crowds.

WRENCH is a multi-scale multi-agent-based model of the dynamic structure and behavior of a crowd in active response to conditions and events in its environment, including those enacted by the engaging security forces.

WRENCH importantly models the emotional responses (including fear and anger) of the crowd in response to the behavior of the security forces; with a special emphasis on the monitoring of security force actions that might represent the use of ‘excessive force’.

Shared convictions of ‘*excessive force*’ have multiple influences on crowd behavior as modeled by WRENCH including: 1) the crowd’s willingness to continue engaging; 2) changes in the crowd’s hierarchically structured constituent social identities, and; 3) the crowd’s perception(s) and the persistency of those perceptions of security force legitimacy (or the lack thereof).

The ultimate goal of WRENCH is to aid DoD crowd engagement planners in defining a suite of ROEs that will accomplish the immediate tactical objective(s), while minimizing the loss of security force and host-nation legitimacy.

This report summarizes recent developments in 1) the *design* of the crucial WRENCH *social identity dynamics modeling* component, as well as developments in: 2) the modeling of the influence, on crowd behavior, of messaging-based engagements; 3) the inclusion, within WRENCH’s core crowd behavior modeling capabilities, of a capacity to model shared goal-oriented behavior; and 4) an assessment of the impact, on the existing WRENCH design, of including a model of advanced crowd sensing/sensor capabilities.

Keywords: *crowd behavior modeling; rule-of-engagement; legitimacy; non-lethal weapon*

Background

Effectively managing an engagement with a potentially hostile host-nation crowd, such that the immediate mission requirements are achieved *and* host-state legitimacy is maintained/supported, has long been recognized as a difficult combination of mission objectives.

In response, the US DoD has instituted a program, the Joint Non-lethal Weapon Directorate (JNLWD), which is producing and deploying a growing arsenal of nonlethal weapons (NLW) that have been developed and/or acquired in the hope of addressing this challenge more effectively. And while these weapons have certainly contributed to the desired solution, their utility has been limited by uncertainty regarding the circumstances under which each weapon *should* be employed. Existing *generic* ROEs tend to address only the most obvious weapon use restrictions, leaving the bulk of the job of defining effective engagement-specific ROEs largely in the hands of ground commanders. Ground commanders generally have limited training and often have limited experience in managing engagements with potentially hostile crowds, which are almost invariably both *complicated* and *complex*, and often apparently idiosyncratic agents in their own right.

Human crowds vary in terms of the state of their physical condition, emotional state, intentionality, and environmental circumstances. Understanding the crowd's state trajectory during security force engagement (and in part because of it) is critical to understanding how it will behave. The objective of this research is to enhance our understanding of these context dependent influences, so as to more capably and reliably achieve our desired mission objectives.

Central to this enterprise is a foundational shift, which has emerged in recent years, regarding the understanding of crowd behavior. The historically simplistic notion of crowd behavior as the product of a simple summation of the effectively homogenous and anonymous emotional expressions of the various collocated individuals, has been replaced by an understanding of crowds as constituted by non-anonymous individuals, *and* dynamically evolving social identity groups, which possess individual *and* collectively shared intentional behaviors which are formed in response to emotionally triggering events that change as the underlying 'personalities' of the crowd's components evolve in real time—i.e., crowds are now seen as being capable of a much broader range of behaviors, including 'intelligent' behaviors, than was once imagined.

One of the key factors determining our influence on a crowd's state trajectory involves the extent to which the crowd comes to regard *us* as intending to *engage* them (i.e., participate in *role reification* with them) versus *control* them (i.e., define *them* as illegitimate and subject to sanctions). How effective the security forces are in negotiating mutually respectable 'boundary' conditions with the crowd (and its various elements) is critical to generating these felicitous outcomes, but doing so can involve some nuanced engagement strategies. Crowds often don't assemble or emerge with recognized narrative negotiating foci, i.e., leaders. Consequently, any specific concrete engagement of the crowd will often both play a role in giving (or denying) a 'voice' to the crowd as well as negotiating a mutually acceptable outcome. Such engagements involve both 'carrot' and 'stick', but where and how we offer these punishments and rewards can make all the difference.

This effort is built upon a previous research effort performed by the Naval Postgraduate School (NPS-17-M177-A) focused on the development of a multi-agent model of the tactical effectiveness of nonlethal weapons in engaging crowds of various kinds and temperaments.

This follow-on effort specifically addressed how the judicious 'targeting' of nonlethal weapons (NLW), on specific elements of the crowd, can felicitously impact both the immediate emotional state and intentional behavior of a crowd.

This, along with the more expansive and enduring sense of resentment, betrayal and/or loss of legitimacy that can be engendered, within the proximal population, and consequently directed at the host-state (which we are supporting) and/or our own defense/security forces, when the crowd is engaged as a whole.

Effective modeling of the influence of selective crowd targeting captures both the contagious effects of localized aversive and opportunistic events, at various scales and impacts (generated by either the crowd itself or by our own engaging security forces) as well as the dynamics of the relative salencies of the collective ‘social identity’ of the crowd (and any constituent social identities) that such engagement events trigger.

This research leveraged and built upon an existing tool called WRENCH v2.2 (Workbench for refining Rules of Engagement against Crowd Hostilities). This effort enhanced the underlying crowd identity dynamics and intentional behavior model, refined the design of NLW effects and related sensor models, expanded the range of modellable crowd scenarios, and explored methods to automate the search for viable/practical optimizing ROE.

WRENCH’s key crowd behavior modeling foundation leverages a multi-agent complex adaptive generative social science approach. One of the key contributions of this work is a clear delineation of the combined temporally-dynamic psychological (cognitive) and sociological (network) influences of fear and anger on emergent crowd behavior. Security Force (SF) legitimacy is seen as being highly correlated with what the crowd perceives/cognizes as ‘excessive force’.

The ultimate objective of this research is to build and deliver, to the JNLWD, a tool that will recommend optimizing NLW ROEs that are both effective in managing hostile crowds and minimize the loss of security force (and/or State) legitimacy. The intent is to inform realistic requirements for system developers and provide guidance on the use of NLWs.

Findings and Conclusions

The ultimate goal of this multi-year research initiative is to refine the rules of engagement that DoD and host-nation security forces employ when engaging with host-nation (potentially) hostile crowds in the service of host-nation legitimacy maintenance/development. Critical to this objective is the development of a crowd behavior model that validly captures the non-linear behavioral responses exhibited by crowds in contact with security forces.

The development of models of non-linear and emergent system behavior is currently as much an art as it is a science. It is often far from clear *which* feedback loops, operating under what conditions, yields the system behaviors that can be observed and directly measured. This is a difficult enough enterprise even when the system is not ‘cognitive’, and consequently not maintaining and evolving its own internal behavior influencing state.

Crowds are, however, not only cognitive systems, but they are also *cognitive* at multiple interacting scales, which are actively evolving internally even as the system (i.e., the crowd) engages with the ‘external’ world (of the security forces). The most promising approach for studying such systems is sometimes characterized as ‘generative social science’.

The goal of a *generative social science* approach is to recreate (often via simple exploration), using a multi-agent bottom-up approach, the observable system behavior and then testing the resulting model against novel situations to evaluate how reliably the model continues to ‘anticipate’ real world behavior. As such, the approach is also sometimes labeled as an ‘anticipatory analytic’ approach.

We are currently, within the generative social science approach to this crowd modeling behavior challenge, in the stage of putting in place the foundationally necessary pieces that must be represented if we are to generate, from a bottom-up processing approach, the collective non-linear crowd behavior that has been historically observed and recorded.

Amongst the key findings of this research during this spiral of development are the following:

On Social Identity Dynamics Modeling Design Principles:

- The same SF coercive act can be regarded, by a crowd, as either legitimate or as illegitimate.
- The crowd, as a whole, will evaluate the legitimacy of SF coercion, in part, as a consequence of independent evaluations made by constituent social identity groups (SIGs) within the crowd.
- Any act of coercion that triggers a ‘sensemaking crises’, in one or more SIGs within the crowd, will likely also have an impact of the size and/or state of one or more crowd SIGs.
- A SIG’s susceptibility to a sensemaking crisis is driven by its *adaptive cycle state (ACS)* [defined by its ethical framing paradigm, norm enforcement effectiveness and resource management potency] and its sense of ‘resiliency’ derived from inter-scale affective trust.
- The ACS of a SIG determines the nature and saliency of the events that will be processed as unexpected, and consequently, be subjected to an ‘emotional assessment’ and a consequent narrative intention generating process that possibly triggers a *sensemaking crisis*.
- The relatively rare characteristics of ‘extraordinary leadership’ (i.e., those by which a constituent agent can help a SIG navigate a *sensemaking crisis*) can be characterized, identified in-situ, and instantiated by training.

A design document describing these dynamically processes and their interaction has now been completed and provided to the customer.

On the core capabilities required for valid crowd behavior modeling in response to coercion:

- The modeling of constituent social identities and their dynamics
- The role of collectively perceived trust dynamic events in the generation of SIG intentions
- The role of SIG intentions in the evolution of the dominant narrative framing of a SIG

All three of these key components of crowd behavior modeling now find a prototype instantiation within the modeling of the WRENCH 3.0 spiral, which was also provided to the customer.

Output of the *modeling requirements reassessment* on key influences driving crowd behavior:

- Coercive SF acts directed towards the crowd and/or its identifiable elements

- Non-coercive informational exchanges between the crowd (or elements) and the SF
- Environmental elements, particularly those that impact a crowd's well-being (e.g., food, shelter, safety, and sanitation)
- Advanced sensors technologies supporting, for example, the rapid identification/mapping of a crowd's emotional state (e.g., angry/afraid) and the crowd's constituent identity makeup. Leadership and spatial distribution are both seen as pragmatically enabling the specification of viable ROEs, which are currently beyond the reach of existing soldier training regimens. They were not, however, seen as requiring substantial enhancement to the existing WRENCH design.

The first and second of these heretofore unidentified factors prompted the development of additional WRENCH design requirements. The critical role of dynamically generated constituent and collective social identities (1) prompted a significant redesign of WRENCH to support creating, modifying and deleting social identities in run-time response to events. The impact of *non-coercive* 'dialogue' between SF-Crowd (2) prompts the need for ROEs that are contextually framed by the current state of the dialogue itself, which is a feature beyond the scope of WRENCH 2.2.

The environmental factors (3) which influence the crowd's sense of well-being were assessed as *influencing* the emotional assessment process, but as not requiring any systematic change to the WRENCH design in order to incorporate. Similarly, the impact of advanced sensors was deemed, while enabling new and efficacious ROEs, to not require substantial changes/upgrades to the design of WRENCH.

In summary, the prime and most notable contribution of this research phase agenda has been the careful development of the complex process by which social identities are created, evolve, and fractionate in real time, in response to the behavioral acts of security forces *and* in the delineation of the central importance of understanding those dynamics for anticipating future crowd behavior.

Finally, we note: Early evidence suggests that *most* crowds are experiencing some degree of what we would characterize as a *sensemaking crisis* before any engagement with security forces. A crowd's engagement with security forces can and sometimes does exacerbate this experience. Extraordinary leaders, capably of managing crowds through such non-narratable experience, can play an outsized role in determining the crowd's ultimate evaluation of the 'meaning' of any necessary use of coercive force. The key to extraordinary leadership seems to hinge on such a leader's understanding of, and capacity to map out, the independent adaptive state trajectory of the crowd's various constituents (including the security forces) and 'tweaking' these trajectories so as to avoid toxic interactions.

Recommendations for Further Research

Further spiral refinement of the WRENCH model design and encoding of a crowd behavioral response(s) to security forces actions are recommended in the service of increasing WRENCH's fidelity in anticipating critical crowd behavior tipping point behavioral states. A significant element of this next spiral should involve *encoding* of the design refinements developed during this phase. Further research and *design* refinements are recommended in support of: the design of ROEs governing crowd message engagement, the potential value of multi-level command and control structures, and the critical role of responsive leadership.

HQMC PROGRAMS & RESOURCES (P&R)

NPS-19-M249-A: Computational Experimentation to Simplify and Optimize a Large-Scale Simulation of Resourcing Marine Corps Readiness

Researchers: Dr. Thomas Lucas, Dr. Susan Sanchez, Dr. Paul Sanchez, LtCol Mary McDonald USMCR, and Maj Stephen Upton USMC Ret.

Student Participation: Maj Kevin Doherty USMC

Project Summary

Marine Corps senior leaders need to allocate service resources to deliver ready units when required to combatant commanders. The goal of this research was to use computational experimentation to provide model-based evidence to Marine Corps' decision makers as they seek policies and investments to achieve force readiness objectives in future years. The Marine Corps' Readiness and Availability Tool (RAT) is a model that provides insight into operational readiness. This research developed an updated version of RAT that facilitates massive experimentation. This new design of experiments (DOE) capability was used to efficiently explore the dynamic interactions of RAT. Analysis of 1,200 simulated readiness timelines shows that in developing a force-wide readiness strategy for the Marine Corps, it is critically important to consider the interactions between force structure, deployment demand, and force-generation-timeline decisions rather than to focus on any single aspect of readiness planning. This executive summary is based on Doherty (2019), which contains the details of this research.

Keywords: *future years defense plan, FYDP, data farming, design of experiments, doe, large-scale simulation, operational readiness, readiness and availability tool, rat, special purpose marine air ground task force, SPMAGTF*

Background

The interactions between resources and readiness are complex, involving thousands of decisions and intermediate outcomes. To help understand the potential impacts of policy decisions on readiness, the Marine Corps' deputy commandant for programs and resources is building a suite of models of operating force elements that propagates the effects of resourcing and policies in the Future Years Defense Plan (FYDP), in order to quantify the readiness of force elements in each year of the FYDP. The objective of this research was to use data farming techniques to improve upon the Marine Corps' ability to provide model-based evidence to Marine Corps' leadership on the potential impacts of policies and investments in achieving force readiness.

Data farming is the use of computers and designed experiments to build and analyze computational models. Recent advances in our ability to explore high-dimensional computational models include greater computational speed, new DOE (Cioppa & Lucas 2007), and data visualization.

The Marine Corp's RAT was selected as the readiness tool to data farm. RAT simulates a process in which both force elements and demand nodes cyclically move through a scheduled steady-state rotation of deployment, dwell, and pre-deployment training. The steady-state rotation can be disrupted by contingency operations that pull force elements in order to fill pop-up needs. RAT utilizes discrete

categorical input variables to facilitate the modeling of different force structures, deployment requirements, force-generation timelines, and contingency mission scenarios.

Findings and Conclusions

This research developed a DOE-enabled update of RAT, and used this new capability to efficiently explore the operational readiness impacts resultant from Marine Corps' decisions regarding force structure and force employment. A total of 1,200 readiness timelines were simulated, with a goal of stressing the Marine Corps' readiness system, in order to find breaking points in its capacity to meet demand. We used basic summary statistics and metamodels to explore the simulation response surface of RAT for factor significance, key decision thresholds, and variable interactions. Some key findings from this analysis are:

- The number of infantry battalions is the dominant factor in determining average home-station readiness. The primary threshold to consider is whether the utilization is less than or greater than 23 battalions.
- Factor interactions are significant in each of the four metamodels developed for this research. Specifically, the percentage of non-ready units which deployed three-way interactions provide insightful thresholds that could be translated into Marine Corps' policy decisions.
- At the Marine Corps' current force structure of 24 infantry battalions, and deployment-demand equal or greater than seven steady state deployments, RAT displays a risk factor of 11% in deploying non-ready units, even if resourcing is provided to ready units in less than nine months. By increasing the force structure to 26, the risk can be reduced to 4.4% and a resourcing requirement of less than 11 months.
- If the Marine Corps were to reduce its Special Purpose Marine Air Ground Task Force deployments to only one, the risk of deploying non-ready units could be reduced to less than 1% at its current force structure. However, if the Marine Corps were to also reduce its force structure to less than 23 battalions, then this risk would increase to 9.8% with a requirement to ready units of less than 11 months.
- A potential error exists within RAT's business rules for sourcing contingency operations, which has been identified for the sponsor.

Recommendations for Further Research

The Marines can leverage several findings from this research toward improving their ability to estimate operational readiness in the future. These include making more of their modeling tools stochastic, and more of their data farmable.

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I MARINE EXPEDITIONARY FORCES (I MEF)

NPS-18-M293-A: Operational Aerial Communication Layer

Researchers: Mr. John Gibson, Dr. Gurminder Singh, Mr. Charles Prince, LCDR Steve Iatrou USN Ret., and Dr. Duane Davis

Student Participation: No students participated in this research project.

Project Summary

This research extends previous Naval Postgraduate School (NPS) Naval Research Program research into the use of aerial layer communications to extend the reach of tactical networks in support of Enhanced Marine Air Ground Task Force (MAGTF) Operations. In particular, this research, through a series of field experiments, continues the investigation and exploration of support for extending survivable tactical networks leveraging unmanned aerial vehicles. Of particular interest are solutions that leverage small swarms of autonomous unmanned aerial vehicles to provide communications on-the-move in satellite and radio frequency (RF)-degraded/denied environments. Extending tactical networks to highly-dispersed or remotely-inserted, fast-reaction forces continues to be a challenge for military and disaster response operations. This research continues the exploration and experimentation of alternative courses of action to address the need for beyond-line-of-sight communications to support Enhanced MAGTF Operations (EMO).

Keywords: *Joint Aerial Layer Comms, unmanned aerial vehicles, UAVs*

Background

Over the past decade, operations in permissive environments have demonstrated the capabilities of America and her partners when they have effective communication. However, end-to-end communication is not guaranteed on the battlefields of tomorrow. This means that we must either sacrifice capability or develop systems designed to operate in this uncertain environment. Many organizations have sought to leverage the possibilities brought by swarming unmanned aerial vehicles (UAVs). This research merges the efforts of two of these organizations to develop a concept that may be of use for future Marine Corps' operations. The first of these organizations is the NPS's Advanced Robotic Systems Engineering Laboratory (ARSENL) program, which has steadily built autonomous swarm capability culminating in the simultaneous flight of a swarm of 50 UAVs (Chung et al., 2016). The second organization is the Australian Defence Science and Technology Group (DSTG), which has conducted research in controlling a UAV swarm using digital pheromones to allow communication ferry nodes to operate in a contested RF environment. This research builds on this previous work in communication ferrying by providing a mechanism to coordinate bi-directional UAV ferry nodes, sometimes referred to as data mules. Bi-directional data ferrying can facilitate friendly force communication, while reducing the message delay inherent in a single-direction system.

Findings and Conclusions

This research focused on expanding the previous work by Australia's DSTG to develop a dual-direction delay tolerant data-ferry system, using an autonomous aerial swarm. In this work, we focused on the mathematical relationship between the two directional pheromones, and implementation of the capability

on the NPS ARSENL swarm. While this research provides a possible method to implement a dual-direction delay tolerant ferry node system, further work is required for the concept to be made suitable for fielding in an operational system. The future work section in this chapter discusses some of the next steps, which might eventually result in a fielded capability for the warfighter.

1. Adjusting Pheromone Values at Reset Creates Even Distribution

Our key finding is that stigmergic control mechanisms can provide evenly distributed dual-direction ferry UAVs, while operating in a RF denied environment. This was achieved through the intentional adjustment of the pheromone values as they are reset; all other findings build upon this concept. Two possibilities were identified for incorporation of the prograde-retrograde pheromone link: first is where the pheromones decay, and the second is where the pheromones reset. Attempts to link the prograde and retrograde systems at the decay location were difficult to control, and this method ultimately detracts from the information implicitly conveyed by the steady pheromone decay rate. Changes at the time of reset proved easier to predict and adjust to affect the global behavior of the system, without negatively influencing the pheromone-based information.

2. Different Types of Ground Nodes

The dual-direction ferry node system operated under different dynamics than the single-direction ferry node system. When a single ferry node system converges, the distance between the ferry nodes remains the same around the perimeter. All ground nodes, then, regardless of location, will influence the ferry nodes to the same equilibrium state. This is not the case for a dual-direction ferry node system, where even distribution only occurs at specific locations around the perimeter. Influence from ground nodes not at one of these locations will actually disrupt the system's convergence, because the equilibrium positions to which these nodes attempt to influence the system will conflict with other nodes' influences.

To ensure convergence, the implementation of two different types of ground nodes for the dual-direction ferry node system, adjusting nodes and resetting nodes, was required. Adjusting nodes are physically located at the preferred equal-distribution points and are used to link the two pheromones. For our testing, we only used one adjusting node; however, it is easily shown that one or more of these nodes placed at equilibrium points will result in system convergence. The second type of ground node was the resetting ground node. These ground nodes only reset the directional pheromone to the maximum value, without regard to the status of the opposite-direction system's pheromone. In this, they function the same way as Fraser's single-direction system's ground nodes. It was noted that any ground node not located at an equal-distribution point must be a resetting node for the bi-directional system to converge. For our testing, all ground nodes, with the exception of a single adjusting node, were resetting nodes. The use of these two types of ground nodes led to a converged visitation time for the adjusting node in ground node layouts ranging from three to ten ground nodes. The visitation time for the resetting nodes varied predictably based upon their location around the perimeter, up to twice the converged visitation time at the adjusting nodes.

3. Universal Adjustment Value

During our testing, we found that each ground node layout had a specific adjustment size that resulted in the fastest convergence time, and that optimal adjustment sizes were unique to that particular ground node layout. That is, when optimal adjustment sizes for one layout were used on other ground node layouts, they did not result in the fastest convergence time or they failed to reliably converge. The possible improvements from these types of adjustments is discussed in the future work section.

After recognizing that there was no universally optimal adjustment value for arbitrary ground node layouts, we attempted to find one adjustment value that resulted in converged ferry nodes for all ground node layouts. For this, we experimentally found that the raw calculated adjustment value, without amplification or reduction, could be used to achieve a converged ferry node system for all tested ground node layouts.

4. Largest Reset Window Led to Fastest Convergence

The window for allowable pheromone values was the other parameter that we tested. The largest pheromone adjustment values occurred when the ferry nodes were least dispersed (most likely immediately after initiation). Since large adjustments shortly after system initiation have the potential to over control the system, saturation limits, referred to here as reset windows, to the adjustment value were tested. We experimented with reset window sizes from the following set of values: 0.3, 0.45, 0.6, 0.75, and 0.9. The optimal reset window size varied between ground node layouts, but for most ground node layouts, the 0.9 window had the lowest average convergence time or yielded convergence times that did not statistically differ from the experimentally identified optimum reset window. Of note, this window size allows the pheromone to increase or decrease by the full size of the adjustment.

5. Advantage of Dual-Direction System

Finally, we demonstrated that a dual-direction system results in lower maximum and average delivery times through both analysis and simulation than a single-direction system of the same size. It was mathematically derived that a message destined for one other ground node travels along the shortest length of the perimeter to its destination, and we experimentally demonstrated that a message destined for all other ground nodes would be delivered faster using a dual-direction system.

Recommendations for Further Research

1. Incrementing Instead of Decrementing Pheromone Values

Choosing the decay rate is key to making the algorithm for this research work correctly. If it is too small, the pheromones decay too slowly, which delays the swarm's convergence. On the other hand, if the rate is too large, the pheromone can decay to zero before the next ferry node visits, and information is thus not properly conveyed to follow on ferry nodes. The swarm will fail to converge if this happens too often during a given run. Use of increasing pheromones, rather than decreasing ones as implemented for this research, would prevent situations where the pheromones do not communicate information and might mitigate the effects of suboptimal implementation decisions. Implementation would require at least two steps. First, the reset value would have to be rethought. The initial thought is it would change to 0.0, but this would prevent dual-direction adjustments unless negative values were allowed. Regardless of whether or not negative values are allowed, a reset value of 1.0 could be retained, or a different positive value could be chosen. Second, the speed calculation would have to be adjusted to accept an increasing pheromone value.

2. Test Algorithm for Moving Ground Nodes

All testing done involved stationary ground nodes. Future testing could seek to apply this algorithm to moving ground nodes. The results from this testing would verify that the concept is useful under more realistic scenarios. Based on our results, the calculated adjustment value and maximum reset window may evenly disperse the ferry nodes, but a converged system is unlikely due to the constant movement of the ground nodes. Testing of moving ground nodes would determine whether further modifications are required.

3. Variations in Decay or Increase Rate

The decay rate for experiments in support of this work was set at a constant rate proportional to the perimeter length. This allowed comparisons between the different ground node layouts. A larger decay rate results in faster ferry speeds, and these faster speeds provide faster convergence. Future testing could determine a better decay rate (or increase rate if the pheromone mechanism is changed per the first recommendation). Efforts along this line of research could also explore potential of dynamic rates decay during each simulation, wherein decay rates change based on system performance or by overt operator action. This could better optimize the decay rate for the given situation or enable system responsiveness to changing operational contexts. While more challenging, such dynamic pheromone rate values might be possible with synchronized clocks and communicated decay rates.

4. Evaluate Pheromone Adjustment Size Tailoring for Given Ground and Ferry Node Layouts

During our adjustment size testing, we found that a specific adjustment size resulted in the fastest convergence for each ground node layout. These optimal adjustment sizes provided a marked improvement over the standard adjustment value, but different ground node layouts did not share this same optimal adjustment size. Further testing might be useful in identifying an analytic means of deriving the optimal value from the number of ferry nodes, the length of the perimeter, and the number of ground nodes.

5. Identify Adjusting Node Transition Mechanisms

We found that the dual-direction ferry node system could only operate using two different types of ground nodes: adjusting nodes and resetting nodes. The use of different types of nodes, however, comes at a cost to the robustness of the system. If this one adjusting node fails to function, for instance, the prograde and retrograde pheromones will be uncoupled, and the bi-directional system will not converge. Development of a more capable ground node that can play the role of either adjusting or resetting node, and detect when a role change is required, will make this system resilient to node failure. One option would be to assign a priority to the ground nodes based on the priority of the ground units that they support. If the ferry nodes make a certain number of laps around the perimeter of the system without hearing from an adjusting node, then another high-priority node can be notified and then assume the adjusting role until the primary node is contacted again. Other mechanisms to address this single point of failure issue are worth exploration as well.

6. Live-Fly Testing to Validate Algorithms in a Real-World Environment

Future live-fly testing will allow for further development of the system. Through the integration of ARSENL and HAIL, and the development of the coupling algorithm, we have provided the foundation for future live-fly testing to refine the operational capabilities of the resulting system. Live-fly testing using three ferry nodes in each direction and simulated ground nodes is planned for June 2018, and future live-fly tests can extend this by implementing actual ground nodes and varying numbers of ferry nodes.

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II MARINE EXPEDITIONARY FORCES (II MEF)

NPS-19-M103-A: The Running Estimate (RE) for the MEF Command Element / NPS-19-N333-A: Provisioning of a Multi-int Fusion Environment in the Era of AI and Machine Learning

Researcher: Mr. Arkady Godin

Student Participation: No students participated in this research project.

Project Summary

The ability to integrate environmental conditions into combat operations is critical to Navy and United States Marine Corp (USMC) battlefield success. Therefore, dynamically extracting and projecting operationally relevant events from data significantly enhances the commander's ability to make informed decisions, as compared to decisions based purely on a theoretical understanding of the events. The framework of our study included requirements for the proposed data architecture to potentially provide environmental data to commanders and troops, one that could garner high-fidelity results for computer-assisted mission planning and tracking of Running Estimate (RE) metrics. These capabilities include execution of high-level, scalable viewpoint of a commander's intent, appropriate for tactical edge mission execution, or at the operational or strategic level.

The research was conducted using a literature review, interviews and discussions with subject matter experts (SMEs), followed by market research focused on commercial startups that are state-of-the-art leaders in data processing. SMEs were selected from the areas of Information/Knowledge Management for Mission Planning, Future Concepts of Operations for MEF, and Subordinate Commands. Additional collaboration with the Navy Digital Warfare Office and the Center for Naval Analysis led the team towards a "thinking chess" approach to tactical maneuver courses-of-action (COA) analysis: a software product created by Stilman Advanced Strategies, based on the Linguistic Geometry (LG) mathematical foundation.

From the research, a knowledge representation (KR) leveraging modern technologies emerged, based on additional considerations of performance and scalability, and the need to support access by decision makers at all levels of warfare. Ultimately, this research study revealed a layered ontology for describing the battlespace in a way that provides real-time decision support, and enables COA development and assessment by human warfighters, and ultimately, by artificial intelligence (AI).

Keywords: *ontology, battlespace, decision, situations, events, entities, courses-of-action, mission planning*

Background

Our research is based on the highly-adopted Observe-Orient-Decide-Act (OODA) Loop developed by Air Force Col John Boyd, combined with the study sponsor's operational background, centered on event-driven decision making. In February 2017, Dr. John Launchbury made an announcement for AI stepping

into the 3rd Wave of AI, which Dr. Launchbury coined as “Contextual Adaptivity.” This announcement coincided with our team’s understanding that state-of-the-art decision making requires an in-context adaptive operational picture. As such, our proposed research hypothesis was formulated as the following: “For decisions to be on-time and informed, situational awareness (SA) must be capable of managing adaptive context of the operational world model by absorbing operational and environmental events. Integrating SA which embraces ‘Contextual Adaptivity’, will empower the ‘Orientation’ phase of the OODA loop. Modern COA would have to utilize event-based representation of the battlespace by using reasoning over knowledge, particularly in terms of maneuvering and shooting in the battlespace, in order to reach adaptive contextual understanding of the SA and SA-driven COA.”

Findings and Conclusions

We considered a commonly used model in data science literature: a pyramid built from the bottom up, transforming from data to information and knowledge, and finally, to understanding. This study attempts to bridge the gaps from the information domain to the knowledge domains and understanding, where cognitive processing is paramount. Early in the study, SME inputs resulted in the observation that events in space and time represent an intersection point between the information/knowledge space and the cognitive space. This observation was critical, as commanders and other decision makers depend strongly on connecting information and knowledge layers to produce the level of cognitive understanding required for decision making. This observation was further augmented by the work of Dr. Mica Endsley, former Air Force Chief Scientist, who developed a SA model for dynamic decision making.

Building on the work of Dr. Endsley, we used the Stilman LG COA engine to extend her SA model for OODA loop application to the MEF Information Group for adaptive decision-making in the battlespace. This engine replaces computationally unscalable search—essentially an endless scattershot of possibilities—for a model that successfully constructs COAs for maneuver and fires, using discrete mathematical calculations which build operationally-relevant trajectories, which are then stored as future-projection events in the LG Zones. The purpose of LG Zones is to support short-term plan sub-strategies to enable advancing the progression of sub-strategies from the starting moves to the final moves. Mission planners may choose from several COA options with different risk tolerance, available within the context of each of the LG Zones. In essence, the concept of LG Zones connects strategy to tactics by computing and combining sub-strategies within and across LG Zones, in order to meet the overall strategy expressed via the commander intent.

Considering the sponsor’s great interest in the concept of the RE, it was a pleasant discovery that LG tracks the RE in parallel with the assembly of selected COA options. The topic sponsors found the COA-Running Estimate Analytical Engine to be a powerful AI technology solution for many applications, including those combat operations requiring maneuvering and shooting functions. Other contemplated areas include: supply chain management, manpower, mission, and rescue. The proposed data strategy then integrates well with the sponsor’s command requirements, and validates our initial hypothesis.

Recommendations for Further Research

The Stilman LG COA engine is an example of a closed-architecture application, given its unpublished LG Zones-oriented Knowledge Base (KB). Our research recommends that the Navy and USMC invest into an open-architecture KB, using Causal Bayesian Network Inferencing algorithms, with a focus on temporally adaptive “situation events” of the battlespace, based on the integration between closed-architecture LG Zones-oriented KB, and open-architecture Knowledge and Causal-oriented KB. This would enable bi-directional integration of the overall knowledge of dynamically evolving battlespace situations, due to full understanding of adaptive battlespace context given contextually rich COA.

NPS-19-M103-B: The Running Estimate (RE) for the MEF Command Element

Researchers: Mr. Brian Wood, Dr. Mark Nissen, and Dr. Shelley Gallup

Student Participation: Capt Christine Abercrombie USMC

Project Summary

The United States Marine Corps (USMC) space cadre strategy is not keeping pace with the requests for and access to space-based capabilities made by the Marine Expeditionary Force (MEF) Information Group (MIG) to Marine Corps Force Strategic Command. Lack of properly billeted and insufficient quantity of space-smart Marines has resulted in the Corps taking a back seat to other services during the development of space policy, which does not promise optimal integration with the future Space Force. Premier assets and space-based capabilities often go to waste due to classification time delays and ignorance of their existence. The Corps relies on a robust request process or the attachment of an Army Space Support Team. By examining the current status of the use of space operations by the MIG, this research will be able to put forth recommendations for bolstering the Marine Corps use of space assets, preparing to integrate into multi-domain command and control (C2) with space information overlays, and finding a more efficient use and billeting, manning, and training of USMC space cadre.

Keywords: *space systems, running estimate, MIG COC, MAGTF IE Ops, COP, space cadre, ARSST, MSST*

Background

The Marine Air Ground Task Force (MAGTF) Information Environment (IE) Operations Concept of Employment (USMC, 2017) introduces a comprehensive approach to fighting and winning in and through the information environment. This approach seeks to extend the maneuver warfare warfighting philosophy into the information space, intending to improve the MAGTF’s ability to coherently plan and execute integrated actions in and through the IE. This requires operationalizing the IE as a maneuver space, commanding and controlling information capabilities integrally to achieve objectives, and providing MEF commanders with dedicated organization, tools, and experts to ensure rapidly advancing information capabilities can be planned and executed effectively via a unified, whole-of-MAGTF functional approach.

However, the Marine Corps is currently not organized, trained, or equipped to meet these requirements in the area of Space Operations. The demands of a future operating environment characterized by complex terrain, technology proliferation, information warfare, the need to shield and exploit signatures, and an increasingly non-permissive maritime domain, all remain beyond the Corps' current capabilities. Indeed, there are inadequate mechanisms in place for the MAGTF commander to comprehensively understand, plan, and execute Space Operations as an integral component of operations. This research will offer recommendations for helping to create such mechanisms.

Findings and Conclusions

Methodology

A series of meetings with US Army and Air Force space organizations in Colorado, as well as at the National Reconnaissance Office in Washington, DC, were arranged in order to get a baseline for how other services address Space Operations. In addition, time was spent with I MEF and its MIG to discuss Marine Space Operations. The Naval Space Operations Course was attended by Capt. Abercrombie (thesis student) in San Diego to provide further background.

Three documents were used as primary sources:

1. An unpublished (soon to be published) I MIG Space Operations Standard Operating Procedures that detail the roles and responsibilities of Space Ops Officers (used with permission of I MIG).
2. The MAGTF IE Operations Concept of Employment (USMC IE COE, 2017), a document which addresses the following:
 - a. Assurance of Enterprise C2 and Critical Systems
 - b. IE battlespace awareness
 - c. The controlling of information warfare capabilities, resources, and activities
3. USMC Order 5400.53, National Security Space Policy (MCO 5400.53, 2009), an order which is used to demonstrate that procedures for the MAGTF space staff are limited in scope and vague in guidance.

Findings

A number of recommendations for improvement are submitted for consideration:

1. If the Marine Corps acquires tactical satellites, then changes need to be made to the current space systems architecture, training, and toolsets.
2. The MIG Information Coordination Center (ICC) is not equipped to support digital interoperability and information flow in the space domain.
3. The future strategy to attack information management problems should be more technology- and training-focused and less concerned with increased manpower.
4. Continue to emphasize the importance of space domain through IE Concept of Employment and visionary space concept documents.
5. A singular information suite must be developed regarding the MIG ICC running estimate.
6. Additional emphasis on space personnel needs to be put into place, given that the USMC space personnel total just 1% of the Army's, while the total force is at 40% of the Army's level. This has led to gaps in billeting and deficiencies in MIG Space Ops information-related capabilities.
7. Specific recommendations have been made for USMC Space Cadre personnel training and billeting in various organizations, including a Marine Space Support Team.
8. An Integrated C2 System design is proposed.
9. Develop link architecture from space apps into a singular Common Tactical Picture.

10. Space Operations need to be developed and improved to provide a bridge between IE Battlespace Awareness and Operations.
11. The following are examples of critical information that would be provided by improved space operations support:
 - a. Signature management in support of military deception and operations security
 - b. Blue, Grey, Red Surveillance
 - c. GPS Degradation

Recommendations for Further Research

Each of the recommendations made in this research should be further examined to incorporate into future operations.

NPS-19-M185-A: Optimized Network Emulation of Signals Intelligence (SIGINT) and Tactical Cyberspace Environments for MAGTF Training / NPS-19-N036-A: CYBER/RF MILDEC in Naval Operations

Researchers: Dr. Imre Balogh, Mr. Christian Fitzpatrick, and Dr. Randy Maule

Student Participation: No students participated in this research project.

Project Summary

The research integrates two previously discrete projects on cyber and electronic warfare. See: [NPS-19-N036-A: CYBER/RF MILDEC in Naval Operations \(page 43\)](#).

III MARINE EXPEDITIONARY FORCES (III MEF)

NPS-19-M107-A: MARFORPAC-Pacific Partner Wargaming

Researchers: Dr. Jeffrey Appleget COL USA Ret. and Mrs. Jane Barreto

Student Participation: Maj Kevin Doherty USMC, Maj Josh Gordon USMC, Maj Joe Moeller USMC, MAJ Gabe Samudio USA, Capt Courtney Thompson USMC, MAJ Jan Lim ADF, MAJ James Streams USA, Capt Pat McKavitt USMC, LT Mansfield Murph USN, Capt Alyssa Renosto USMC, MAJ Jared Kassulke USA, MAJ Michael Culligan USA, Maj Tyler Oldham USAF, Maj Daniel Gipper USAF, LCDR Sam Lehner USN, MAJ Robert Page USA, LT Jason Carminati USN, and LT Brian Bird USNR

Project Summary

Through wargaming and analysis studies, this research examined U.S. Marine Corps (USMC) and U.S. Navy (USN) cooperative missions with allied and partner nations in the South China Sea (SCS). The wargames were conducted to familiarize wargaming participants and observers with Marine Forces Pacific (MARFORPAC) USMC and USN expeditionary capabilities, allied and partner expeditionary

capabilities, concepts for joint and coalition employment, and to assess potential locations and logistical requirements for expeditionary operations. Several wargames and Naval Postgraduate School (NPS) courses formed the research activities, including: MARFORPAC-MCWL-NPS workshops, NPS student team designed wargames from the OA4604 Wargaming Applications course, and NPS student team mini-studies from the OA4602 Joint Campaign Analysis course. Our analysis identified technological and logistical gaps in current campaigns, and provides recommendation regarding communications and procedures across several USMC and USN joint operations.

Keywords: *wargaming, campaign analysis, expeditionary advanced base operations, EABO*

Background

The USMC and USN have a long history of working with allies and partners in the Pacific. This research project leveraged relationships forged with USMC and Australian Defence Force (ADF) personnel, and provided additional opportunities to enhance the strong ties between the groups. Additionally, numerous Talisman Saber exercises and past NPS wargames formed the foundation for this research.

Findings and Conclusions

Given the USMC strategy for the force required to operate in the 2025 environment, work focused on providing and determining the Marine Corps' ability to affect change and support Phase 0 (shaping) activities that set the conditions for follow on actions. Wargames were designed to assess MARFORPAC's capabilities and limitations during phase 0 (shaping operations) and phase 1 (deterrence operations).

We looked at the following key issues for all wargames conducted and described in the following sections:

- Key Issue 1: How is the United States' posture enhanced in the region?
- Key Issue 2: How are US allies and partners reassured in the region?
- Key Issue 3: How can the US deter and deny adversaries in the region?
- Key Issue 4: How can the US reduce tensions in the region?

Australian Defence Force (ADF)-USMC Interoperability Wargame:

This wargame was designed to assess the capabilities and limitations of combined USMC/ADF command and control of fires ashore during amphibious operations. Our analysis indicates that increased interoperability depends on constructing a common language, tactics, techniques, and procedures and rules of engagement (ROEs). In order to better facilitate joint operations, communication and information systems (CIS) interoperability must improve, with particular attention paid to the mission partner environment (MPE) as the center of gravity. Additionally, CIS shortfalls and gaps in response to command and control (C2) of maneuver forces and fires have been identified. We also determined that for successful maneuvers, call for fire missions between allies should be seamless to the small unit leader sending the request. For this to occur, weapons employment and release authorities must be well known by all forces. This could be achieved in part by establishing a common tactical ROE, as well as a common set of standard operating procedures for sensors, shooters, and decision authorities. Additionally, exchange of position/location/information (PLI) data is recommended through the MPE at MEB level; to accomplish this and remove latency issues, PLI data must be unrestricted between coalition allies. Lastly, in an effort to reduce logistics burdens, future fire systems should utilize common ammunition.

MARFORPAC Wargaming Workshop Wargame:

This wargame analysis was designed to facilitate coordination of Marine surface fires in support of sea denial in an assigned sector across domains, by identifying the C2 architecture for a Marine Corps Task Force (TF) operating within a Composite Warfare Commander (CWC) construct. Within the analysis, we looked specifically at how the TF integrates within the CWC construct, and components of the “kill chain” process. Our findings are based on a one-hour wargame demonstration. When analyzing how the TF integrates within the CWC construct, we determined that joint interoperability is critical to C2 and the CWC construct. Likewise, the CWC needs to clearly understand Navy specific roles and responsibilities, and several Navy liaison elements and naval capabilities are needed (e.g. anti-submarine warfare) to support larger maritime operational responsibility. In turn, USMC may or may not have the same principal warfare commands as its naval counterparts, but the Marine Corps can task organize to achieve the same objectives. Additionally, to engage the target with the right weapons system, defense in-depth/cross boundary TF commander coordination is necessary. We determined that while the existing USMC “kill chain” process is in line with joint doctrine, it is limited by organic intelligence, surveillance, and reconnaissance. However, these factors can be mitigated by assignment of forces or joint capability. Lastly, coordination with other CWCs will ensure redundancy in layered capabilities and produce desired effects.

Pacific Defender 2020:

In this era of great power competition, and in the event of a conventional conflict in the South China Sea, Marine Forces Special Operations Command (MARSOC) must examine its abilities to shape the Philippines Islands Area of Operations; it must deter competitors throughout the contact layer, while setting conditions to dominate through the blunt layer. Our findings show that presence in key regions is crucial; therefore, regional, cultural, and language expertise are essential to success. An unconventional warfare campaign set favorable conditions in the Philippine archipelago, which helped seize control in regions and bolstered influence. However, identifying gaps in continuity and sustainment in regards to cultural education and language proficiency in the SCS area of responsibility (AOR), will bolster MARSOC capabilities in the SCS AOR, which in turn, will strengthen its ability to shape the operational area for major combat operations. Similarly, expanded intelligence will provide an operational advantage in the contact, blunt, and surge layers. Also, the ability to construct plans and arrangements directly, with a host or partner force, would allow MARSOC to rapidly consolidate their gains in contingency operations, although the maturity of MARSOC teams must be trusted in order to reach tactical or operational arrangements.

MARSOC Indirect Wargame:

In the event of conventional combat operations in the blunt layer, this wargame modeled actions MARSOC can take in the contact layer (scoped to the Philippines and adjoining seas) with indigenous Armed Forces of the Philippines (AFP) partners to secure advantages and deter Chinese influence, and to best posture Marine Air Ground Task Force and other conventional forces. Our analysis shows that it would be beneficial to pair tactical efforts with larger/long-term interagency and whole-of-US Government strategy, and nests efforts with AFP plans and initiatives. There is also a need for increased C2 and intelligence with MARSOC during inter-deployment training cycle and on deployment. We also recommend varying the location and timing of joint combined exercises, as advantages to doing so outweigh the counterintelligence and operational security threats.

Recommendations for Further Research

Wargames and workshops provide valuable insights into USMC and USN expeditionary capabilities, and joint and coalition capabilities, to promote assessment of logistical requirements for expeditionary operations. Further operations research is required to better comprehend how the Marine Corps and Navy can interoperate more effectively to establish and maintain sea control in any maritime environment.

MARINE FORCES CYBERSPACE COMMAND (MARFORCYBER)

NPS-18-M087-A: Development of a Theoretical Framework to Anticipate an Imminent Cyber Attack

Researchers: Dr. Bryan O'Halloran, Dr. Anthony Pollman, and Dr. Alejandro Hernandez

Student Participation: CDR Brian Connett USN

Project Summary

Trustworthiness is often used as a synonym in the field of trusted computing, and is predicated upon the security policy of a system. Preference-based trust and trustworthiness is, however, a larger concern of systems designers, and they must include dimensions that go beyond security policy. This research expands the current field of research to examine the trustworthiness preferences of the stakeholders. The framework presented establishes a combined method of decision-making, that both assesses and informs design motives, to improve the overall trust of a system. Including the subjective comparison of stakeholders, this framework will identify and evaluate the true consistency of a design. Additionally, expected utility axioms are used as checks to ensure a rational decision-making process. The strength exists in the empirical values that reflect those preference-based trust components, which affect the overall system design. A random index extension of previous hierarchy process research is also introduced, which provides the capability to address consistency in large systems. This work strengthens the current conceptual design process by informing design using aggregated modalities.

Keywords: *trustworthiness, combined decision making, expected utility theory, conceptual design, systems engineering*

Background

A conceptual design framework is offered to capture a new approach that gathers non-functional requirements (NFRs), in order to assess and improve the full scope of trustworthiness at any systems complexity, whether that complexity is dynamic or structural. This framework is designed to evaluate viewpoints. The evaluation focuses on the use of knowledge through axioms, analytical hierarchical processes, and modeling techniques used in the development of a complex system.

Several researchers continue to populate the systems engineering (SE) knowledge areas addressing the handling of NFRs. Through a qualitative approach, NFRs are identified, rationalized, refined, correlated and operationalized.

This rational process assists in the decomposition of a system's non-functional areas, identifying ambiguities and the other regions of potential downfall. This Chung framework establishes the tool set necessary for designers to accommodate many different applications. The challenge with this stand-alone decomposition, as noted in the SE Vision 2025, is that the complexity of heterogeneous systems is rapidly growing, while the capability to mitigate flaws in design is diminishing.

Moreira, et al. make two explicit observations: first is that it is difficult to represent how the attributes of NFRs can affect several requirements simultaneously, and second, since the representation and allocation are not supported from the requirements stage to the implementation stage, some engineering principles can be compromised. A novel extended SE design methodology is one that allows translation of customer non-functional requirements needs. Most importantly, for this extended methodology is the mapping of requirements to independent systems. The independent systems, in this case, bear NFRs critical to its exclusive operations. However, these NFRs are not necessarily influencing, or influenced by, neighboring NFRs. Exclusive requirements are the focus of this design methodology and allow for sufficient assignment without affecting neighboring systems nodes. It is appropriate to apply the nodal design parameter across compositions as necessary.

Findings and Conclusions

Literature Review:

This work contributes to the growing body of knowledge of SE and attempts to garner further organization of design considerations through lifecycle stages and lifecycle processes. The result is a model-based systems engineering framework process to develop, evaluate and influence systems architecture decision-making to aid in the design of an optimally trustworthy system, along with an extended definition of trustworthiness for use within the SE community. The definition will allow a systems designer to capture a larger range of NFRs, both in a qualitative and quantitative nature.

A significant part of the research proposed is an assurance mechanism and framework to capture the total stakeholder measure of trustworthiness. There are current rigorous methods to properly capture the stakeholder's requirements, but limitations, however, are found in the complexities of the relationships between those requirements. This research will expand the definition of trustworthy to include the detail of the systems as desired by the customer, which requires a tool and methodology able to measure the consistency and partial ordering of many pairings. The contribution of this work is a framework tool that will capture those requirements through a qualitative process, order those pairings, and create an analysis tool to inform the decision process, helping to improve the overall trustworthiness of a complex system. The final contribution of this work is a modeling tool simply meant to validate the findings of the trustworthy definition. This agent-based model will incorporate the significant effects of the system design methods section into a simulation and model. This model validates the analysis, but also serves a tool to help further strengthen the decision process behind the face-validating phases.

Systems Engineering Process:

The National Institute of Standards and Technology (NIST) identifies a theoretically optimized solution that exists for a protective design strategy, which is balanced across reactive and proactive processes. A proactive loss strategy "includes planned measures that are engineered to address what can happen, and

handling failure regardless of the failure results. . . A reactive loss strategy assumes . . . consequences will occur (Donegan & Dodd, 1991) and response actions shall include mixed interactions of systems assets. The foundational theories and technological components, elaborated into and integrated through sound engineering methods are critical to achieving a successful (proactive or reactive) strategy in identifying methods to improve a systems trustworthiness. The criticality is rooted in addressing the challenge of complexities caused by expanded features and combined mechanisms (i.e. self-adaptation, fault models, verification, probabilistic analysis, et cetera) (Dodd, Donegan & McMaster, 1993). In its considerations for a multidisciplinary approach in the engineering of trustworthy secure systems, the NIST developed an engineering framework by which systems engineers can leverage many security specialties and focus areas that contribute to systems security engineering (SSE) activities and tasks” (Donegan & Dodd, 1991). The guidelines provide considerations that the engineer should examine at each point within the design cycle, and towards many types of systems. This leads to a concept of trustworthy functionality that includes the capability to activate proactive and reactive protections. The product of the Science and Practice of Engineering Trustworthy Cyber-Physical reports, that developing engineering methods for trustworthy systems is absolutely the key challenge. . . ” and we need to ensure that we can justifiably trust that these systems will actually work as needed”(Saaty, 2008). The emergent behavior of cyber physical system of systems (CPSoS) that result from current SE methodologies is evidence that the design process is inadequate to ensure trustworthy CPSoS. Securing the functionality of CPSoS is further complicated by the heterogeneity of its elements. This heterogeneity requires that the engineers address the shared controls and feedback’s between uncommon elements and information streams. The shared characteristics offer opportunity of disruption when those common links are not coupled properly. Finally, emergent behaviors of already implemented systems can be both desired and undesired, regardless of design. This research will contribute to the advancement in the field of systems engineering towards engineering design tools capable of improving the predictability of vulnerabilities to inform the overall design process.

Model-Based SE Design:

To determine the overall trustworthiness of a complex CPSoS, it is critical to consider several methods of engineering design. Traditionally, translating a customer needs into requirements, through physical realization and into an application leans on processes that are largely dependent upon functional requirements. There are, however, no strict rules in design that dictate the use of functionality as the fundamental approach. Since no strict rules exist, NFRs will be used contrary to the traditional use of functional requirements. In particular, trustworthiness is a relatively defined term relying on face-validity methods from over 100 non-functional requirements identified in related research. A limited-design method with Analytical Hierarchy Process (AHP) is tested using this nonfunctional requirement of trustworthiness to build a framework approach. The aggregated measurement is used to determine where it is best to focus design efforts in the concept stage.

Analytical Hierarchy Process (AHP) Heuristics

To inform the decision-making process, the AHP is one of many tools available to organize and analyze complex systems. Concerns are that large systems need more diligence centered on the relationships of systems elements, rather than the elements individually or the whole system. In our research, we explore a few areas: 1) the use of the random number generation for the random index (RI) 2) the use of a true-zero scale, 3) the use of a infinite real number scale, 4) introduction of a decision-making heuristics.

To illustrate, this research uses the same mathematical process to determine a RI in separate manners, based on 1) including a second value of 1 to remove previous bias on that scale, 2) include the value of zero to induce a magnitude measurement of comparisons, and 3) expanding the set to include infinite values.

Using a random sample from a uniform distribution gives a good representation of the worst-case scenario of inconsistency in developing the random matrices that will be used in measuring the consistency ratio. The worst-case scenario evolves from an inconsistency stack-up calculation that represents the cumulative effect of randomly selecting pairwise ranking across system requirements. The author of this paper has taken the step to address deliberate ranking of systems using expanded ranking process.

Recommendations for Further Research

This research will continue with the Marine Forces Cyber unit to apply framework to an existing design. This will allow the systems owner to understand the sufficiency of non-functional requirements allocation across of live complexity.

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MARINE CORPS COLLEGE OF DISTANCE EDUCATION & TRAINING (CDET)

NPS-19-M159-A: Deep Analytics for MarineNet with Personalized Learning - Using the Pilot Data (Continuation)

Researchers: Mr. Walter Kendall, Dr. Ying Zhao, Dr. Magdi Kamel, Mr. Riqui Schwamm, and Ms. Ali Rodgers

Student Participation: Capt Anthony Rybicki USMC

Project Summary

Our analysis of the pilot data demonstrated the potential utility of various analytical tools for measuring Measures of Effectiveness (MOE) for the MarineNet Learning Management System. We used many visual analytic attributes, including learning tools such as Tableau, Orange, Jump, MATLAB, D3, Python SciPy, Plotly, Pandas, NetworkX, RapidMiner, R, Octave, WeKa, and Google to demonstrate the potential of

these analytics to provide metrics to MoE that are tied to learning outcomes.

Keywords: *artificial intelligence, AI, machine learning, ML, deep learning, DL, intelligent data analytics, le*

Background

Previously, in Phase I of the project, we investigated the College of Distance Education and Training (CDET) learning management system (LMS) needs in order to identify the significant capabilities, and subsequently, identify the learning and knowledge transfers and MOEs within MarineNet. We identified MOEs based on our research of accepted pedagogical theory and practice, specifically MOEs with respect to content, learner-content interaction, and learner profile. The resultant analytics based on the MOEs and reports can be used to inform stakeholders such as instructors, sponsors, and developers of how best to enhance the learning experience and content efficiency, in order to improve knowledge retention by MarineNet learners. This research will help CDET determine and define appropriate electronic learning (or distance/distributed learning), MOEs, and how best to appropriate the significant funding spent on distance learning.

Findings and Conclusions

Our analysis of the pilot data demonstrated the potential utility of various analytical tools. We used many visual analytic attributes, including learning tools such as Tableau, Orange, Jump, MATLAB, D3, Python SciPy, Plotly, Pandas, NetworkX, RapidMiner, R, Octave, WeKa, and Google.

Part of the MarineNet currently uses Moodle (2010) LMS, and while Moodle does not contain the comprehensive required data elements for MOEs, it does include the essential student learning results (part of student profile data) and learning behavior. Moodle data from three different classes were used (BCOC 1-19, LCC 1-19, and LCC 3-18). Two types of data were extracted, which highlight the student learning behavior (class logs) and student profile (grades). The anonymized logs included how each student interacted with the website, such as content viewed, videos viewed, etc., grade data, which included with quiz and final grades, and the number of forums and discussions participated in by students. The class logs and grades were joined using the user names, before any data pre-processing. Our thesis student, Captain Anthony Rybicki, played a critical role as a subject matter expert on MarineNet. He also understood the meaning of the data fields collected by Moodle, and was instrumental in extracting sample data from Moodle.

We used two methods to present the data numerically and visually: exploratory data analysis (EDA) and predictive models. With EDA, the data analyst may find useful patterns or trends that better makes sense of the data, while predictive models can predict a student's grade or other performance attributes. The four independent variables of student activity selected for initial EDA included: content page viewed, course module viewed, course viewed, and discussion viewed. These four attributes had the highest coefficients of variation, and were selected because the higher variability may be the source of variability with student grades, and therefore, possibly correlated.

We identified Tableau as one of our visualization tools, which is widely used by business users to generate insights from business data. Tableau views a number of specific events to highlight different learning behavior, such size of the rectangles, and final grades (color) for each student. In addition, we identified that Excel Analysis ToolPak includes multiple regression tools, as well as other powerful exploratory tools.

However, there were only 65 observations and the analysis goal was to demonstrate how generated data from an LMS could be initially analyzed.

As an Excel residual plots shows a probable non-randomness, this suggests a better fit for a non-linear model.

The learning tool Orange can be used both as EDA and as a predictive model, as it features a visual programming front-end for explorative data analysis and interactive data visualization. Orange consists of data and pre-processing tools, visualizing tools that include statistical functions, implementations of many advanced statistical and machine learning algorithms, and Pearson's correlation, which quickly identifies correlations between attributes. However, Orange shows "content page viewed" and "course module viewed" which are almost synonymous, and therefore one or the other would likely not be used in the analysis. Overall, the predictive model features of Orange can be used to improve online learning in order to help students improve their behavior or obtain more personalized content, and therefore receive better learning results. To this effect, Orange includes a user-friendly visual workflow for building a typical machine learning model of decision trees (Orange 2019) for a predictive model of grades.

In summary we showed a use case, using the sample data of the MarineNet CDET website, for how to design MOEs that can guide the collection of big data, analyze website behavior data such as clickstreams with performance assessment data, and therefore, measure all stakeholders' interests and results for an e-learning organization. We also showed the processes and tools for exploratory and predictive analysis.

More specifically, based on accepted pedagogical theory from Bloom's Taxonomy and the Kirkpatrick learning model, we identified 36 MOEs and how to measure them, and identified four categories within said MOEs that can be mapped from learning management systems: content alignment data (content aligns with course objectives and learning outcomes, student profile data (including previous knowledge of the topic), learning result data (grades and assessments), and student learning behavioral data (how a student interacts with a LMS content). We showed with open source tools, even if an LMS doesn't support metrics "out of the box," data can be collected to support many of these MOEs measured by open source analytics. Additionally, various analytic tools can provide useful metrics for the sponsors (how effective is the platform in transferring knowledge) down to the instructor.

Recommendations for Further Research

With respect to CDET, further research could include a data collection strategy that would align with learning outcomes, such as higher levels of learning that require critical thinking. For example, student reports could be processed using Natural Language Processing, and potentially measured in terms of critical learning. Additionally, it would also be possible to tag specific questions in exams in terms of the questions that support various learning outcomes. Overall, a proactive approach to data collection and analytics that would specifically support MOEs would be beneficial in terms of informing program managers, instructors, and students.

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MARINE CORPS COMBAT DEVELOPMENT COMMAND (MCCDC)

NPS-19-M268-A: Creating and Maintaining a Specialized Occupational Force: Marine Information Environment Operations

Researchers: Dr. Kathryn Aten, Ms. Anita Salem, Dr. Marco DiRenzo, and Ms. Sally Baho

Student Participation: Maj Jason Wahl USMC and Capt David White USMC

Project Summary

Specialized occupations, because of their small size and unique skill requirements, offer status and association with an elite community. However, these very characteristics pose challenges for talent management. This mixed-method study investigated drivers of occupational and organizational commitment among operations information warfighters, and explored the factors that influence the development of information operations (IO) expertise. Analysis of interviews informed a literature review, a literature review elaborated the interview findings, and a survey investigated the findings with a broader sample. Overall, the analysis shows that IO warfighters do not attain expertise by the end of their tour, and additionally, IO warfighters are committed to the Marines, but less so to the IO occupation. Enlisted Marines with a psychological operations (PSYOPs) military occupational specialty (MOS) scored higher on commitment than IO officers, who lack an IO career path. The findings support the proposition that the degree to which Marines perceive they are promotable drives occupational commitment to IO, which in turn, drives their desire to remain in IO. Increased time in IO could positively influence the development of IO skills. To support the short-term development of IO expertise, leaders should do the following: create a promotability-commitment feedback loop, design a professional pipeline, leverage pride in mission to build pride in the profession and increase commitment, improve IO skill development and knowledge sharing, and improve the selection process. In the long term, IO skills should be strengthened within command leadership.

Keywords: *information environment, organizational commitment, occupational commitment, talent management, community capacity, expertise.*

Background

The effectiveness of the Marine Corps in the future operating environment will require a robust command and control (C2) system that is integrated with naval operations and the joint world (USMC, 2019). To improve the effectiveness of C2, the Marines have created Operations in the Information Environment (OIE) to help unify network operations, oversee upgrades to the technical infrastructure, and improve the survivability of command and control in contested conditions (USMC, 2019).

IO is the ability to “modify the behavior, influence the decisions, or support the actions of friendly, neutral, and hostile actors” (USMC, 2019). At the lower end of the conflict continuum, information operations are often the primary means of producing effects in a volatile and uncertain operational environment.

Because of this volatility, IO requires a complex set of skills for analyzing the environment, skills that include the “assessment and analysis of the cultural, political, social, and economic factors that influence the objectives and behaviors of key actors in a conflict” (USMC, 2019).

A 2019 study conducted at the Naval Postgraduate School identifies two concerning issues with the management of OIE warfighters. First, the authors conclude that OIE forces attain proficiency just at the time they are required to transition back to their primary military occupation (PMOS) (Cybulski & Yarbrow, 2019).

Second, the 2018 study found that, because there is no PMOS, there are few command opportunities in OIE. Only 2.4% of colonels in fields that do not have a domain-expert career path were promoted, because promotion is not possible absent holding a lieutenant colonel command (Cybulski and Yarbrow). IO warfighters thus have a limited time to develop and utilize their specialized expertise.

The mixed-method study reported here answered the following questions: What are the drivers of organizational and occupational commitment among Marine OIE warfighters? What are the best practices for recruiting and retaining information specialists? What are challenges/opportunities for managing talent in a Marine OIE MOS and how should they be addressed?

Findings and Conclusions

To answer the questions, the research team conducted interviews, a literature review, and a survey of Marines with experience in IO. The study followed a grounded, iterative approach whereby initial phases of the research informed subsequent phases (Teddlie & Tashakkori, 2009). Initial analysis of the interviews informed the literature review, the literature review elaborated the interview findings, and the survey confirmed the findings with a broader sample.

The research team conducted 13 in-depth interviews lasting approximately 40 minutes each. The team surveyed Marines holding IO relevant MOSs. A total of 159 Marines completed surveys, and the research team analyzed interview transcripts using software-supported thematic analysis. The team conducted quantitative analysis including descriptive statistics, correlational analysis, comparison of means, and mediated regression.

An effective OIE requires a level of proficiency that goes beyond traditional warfighting skills. IO warfighters require a portfolio of competencies, which can be acquired by selecting the right people, developing processes for skill building, driving commitment, and building a professional pipeline. Our integrated analysis resulted in a conceptual model that suggests increasing IO warfighters’ perceptions of the value of their experience to their promotability may serve as a key lever to drive expertise and, thus, the overall performance of OIE.

The findings support the proposition that the degree to which Marines perceive they are promotable drives occupational commitment to IO, which in turn, drives their desire to remain in IO. Therefore, increased time in IO could positively influence the development of IO skills. To support the short-term development of IO expertise, leaders should create a promotability-commitment feedback loop, design a professional pipeline, leverage pride in mission to build pride in the profession and increase commitment, improve IO skill development and knowledge sharing, and improve the selection process. In the long term, IO skills should be strengthened within command leadership.

The threat posed to our national security by information warfare calls for specialized information warriors to defend our national interests. Specialized occupations, because of their small size and unique skill requirements, offer status and association with an elite community. However, these very characteristics (small size and unique skillsets) also pose challenges for talent management. This study offers recommendations for improving talent management of Marine IO warfighters. The findings are directly relevant to Marine OIE and, more broadly, to other branches of the DoD which are seeking to manage specialized talent.

Recommendations for Further Research

This study recommends actions to develop a professional pipeline, along with increasing commitment and skills. Future research should explore environmental and organizational drivers, and impediments to change that will affect the implementation and maintenance of an IO force. Action research could support the development of specific alternatives and investigate: What effects do internal and external stakeholders require? What are internal and external levers, barriers and likely effects of potential organizational changes? How can the effects of potential organizational changes be measured?

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MARINE CORPS SYSTEMS COMMAND (MARCORSYSCOM)

NPS-19-M244-B: COTS Solution for Adaptive Communications Paths Using Tactical Handhelds

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Student Participation: Mr. Shruthik Musukula CIV, Mr. Daniel Duan CIV, and Ms. Samantha Batson CIV

Project Summary

The use of commercial off the shelf (COTS) handheld devices in the tactical environment is increasing every year; however, the Marine Corps leverages very little of their wireless capability. By leveraging the use of such radio waveforms and protocols such as Bluetooth, WiFi Direct, WiFi, and cellular, the "tactical handheld" could change the communications domain, as our next engagement is likely to be in a satellite denied, bandwidth-limited environment.

This study seeks to ease the burden of the warfighter, while maximizing the use of lightweight, portable devices, by demonstrating how information and communications can be shared across various waveforms and standards, routing information to the intended recipients, all in a fully automated fashion. In this research, we considered a particularly promising new architecture: Named Data Networking (NDN) (NDN, 2019) (Jacobson, Smetters & Thornton et al., 2009). The central observation of NDN is that users are primarily interested in content, rather than machines or end-points. Of particular interest to our problem domain, researchers have developed a multi-user, serverless, infrastructure-less, peer-to-peer text chat application, ChronoChat (Zhu & Afanasyev, 2013). For these reasons, we chose to evaluate NDN and ChronoChat further to characterize their performance suitability by installing and testing the software. The purpose of this project is to provide the Marine Corps with both a concept of employment and also the tools, processes, and procedures required to engineer and support tactical wireless communications.

Keywords: *infrastructure-less communications, handheld devices, commercial off the shelf devices, COTS devices*

Background

There is a tremendous opportunity to exploit the advanced capabilities of mobile devices, including networking, processing and sensing, in order to increase the safety of our troops and to reduce the loss of life and property during missions. Our military often operates in austere environments which lack computing and communication infrastructure, with little or no ability to access or share vital information. This frequently leaves them in dangerous situations; however, by exploiting the new capabilities of mobile devices, we can overcome these challenges.

This project aims to capitalize on the advancements of networked mobile devices to enable our military personnel to operate without having to rely constantly on external infrastructure. Therefore, our research explores how mobile devices can self-organize into peer-to-peer networks that transmit signals among themselves, but do not rely on external wireless or cellular infrastructure. Our focus on austere network environments and military needs is unique.

The acute need for infrastructure-less communication begs the question as to whether the Internet Protocol (IP) fundamentals and network architectures are appropriate for military applications. For instance, IP assumes the availability of a contemporaneous and reliable end-to-end path, name lookup services, and routing and forwarding infrastructure (Clark, 1988). As one military example where these assumptions may not hold, a deployment of troops may: i) experience connectivity disruptions as they move, ii) not have the ability to resolve names to addresses, or iii) not have a connection to dedicated network infrastructure.

Such challenges are not wholly unique to the military, as ad-hoc vehicular networks may be important in a world of autonomous transportation, or when consumers lose infrastructure service during natural disasters and emergencies. Further, many regions of the world simply have no infrastructure. Emerging research reconsiders the ways in which networks are used, and will be used, in order to develop new architectural paradigms to accommodate such challenges.

Findings and Conclusions

IP was developed in an age of time-shared machines, where users needed to login to a specific machine to accomplish work. Whereas the IP architecture is centered on sending packets addressed to specific machines, in today's network, we are generally agnostic about where the content comes from, and instead, rely on search engines, e.g., Google, to find content, and Content Distribution Networks, e.g., Amazon Web Services and Akamai, to replicate and serve data. In this model, a user does not necessarily care about what machine (or machine IP address) she obtains a copy the content from, but rather, is willing to receive it from any replica so long as it is authentic and unaltered.

NDN is an architecture that fundamentally changes the network service from delivering packets to a specified destination machine address, to fetching data with a specified name, so content, rather than end hosts, is named. This architecture has many potential benefits, including the ability to support infrastructure-less communication.

Consider, for example, two users on a subway train who wish to download the day's New York Times newspaper. Today, the mobile devices of these users must find a network attachment point (e.g., the cellular network), find the hostnames responsible for hosting the New York Times (e.g., via a Google search), lookup the machine address corresponding to these names (e.g., via the Domain Name System), and fetch the content from the machine on the wired Internet. Instead, with NDN, if one user already has a copy of the newspaper, the second user could simply obtain a copy of the newspaper directly using a point-to-point transfer; thus, nodes can be both consumers and producers of data, and there is no assumption of infrastructure or server support. Indeed, similar to a military situation of deployed troops without connectivity, the two users on the subway may not have any cellular connectivity while underground, but the user can still obtain the newspaper from her peer.

As a National Science Foundation (NSF)-sponsored project (NSF, 2010), NDN is open-source and available for testing and evaluation (and refinement).

Thus, NDN meets several of our desired criteria. It is:

- i. link-layer agnostic (such that communication between two nodes can be through a third, and the links need not use the same technology),
- ii. does not require infrastructure or servers to run,
- iii. can tolerate disruptions and disconnections,
- iv. is open-source licensed, and
- v. has an existing chat application.

Recommendations for Further Research

There are several opportunities for future research. For example, work to support field testing of NDNs could explore the ability to employ NDNs under conditions of military operations and develop a detailed concept of employment of NDNs. Also, while portions of this research indicated that NDNs would be useful for military operations, military specific extensions to the basic architecture of NDN should be investigated.

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NPS-19-N248-A: Mission Scenario Generation and Characterization to Support Acquisition Decisions for Long Range Precision Fires-Maritime (LRPF-M)

Researchers: Dr. Kristin Giammarco, Mr. Mikhail Auguston, Mr. Ross Eldred, and Ms. Marianna Jones

Student Participation: Mr. John Quartuccio CIV

Project Summary

Often, system requirements are shaped around operational scenarios that capture the anticipated uses for a system. However, this method becomes problematic when the number of anticipated and tested scenarios are far less than the number of scenarios that the actual system may potentially encounter. During early design phases, these missed scenarios often result in missed requirements, causing systems to fail to meet needs and tacit expectations. This research helps with conception and consideration of system requirements early in design, demonstrating a new and far more comprehensive approach for mission scenario generation and characterization. Using source data provided by the topic sponsor's delegate, we created a Monterey Phoenix (MP) behavior model for a baseline littoral operation mission. We then enumerated dozens of alternative possible flows for that mission, given events that can occur in the system (a platoon), and in the system's environment. Our findings show how the MP model exposed assumptions about the operation, which were codified into formal logical and simplifying constraints. When these constraints are applied together, a reduction in the number of valid scenarios at scope 1 from 105 to 22 occurred, and when the constraints are considered separately, each can be used to drive the conception and consideration of mission and system requirements.

Keywords: *scenario generation, requirements analysis, formal methods, behavior modeling, Monterey Phoenix, MP*

Background

MP (Auguston, 2009) is a Navy-developed formal language and approach for modeling systems, software, hardware, people, organizational, and/or environmental behaviors and their interactions with one another (Auguston & Whitcomb, 2010).

MP can be used to describe high-level operational processes, other business processes or architecture designs, and can support behavior descriptions down to a detailed design level (Auguston, Giammarco, Baldwin, Crump, & Farah-Stapleton, 2015). It differs from other behavior modeling approaches by using lightweight formal methods (Jackson, 2012) to generate a scope-complete set of scenario variants from system behaviors and interactions within and among independently specified systems. Scope-complete means the set of automatically generated scenarios is exhaustive up to a user-defined number of loop iterations (the scope limit), which is usually between 1 and 3. This degree of completeness, even for small scopes, results in an entirely new way to conduct verification and validation (V&V) of human, system and software behavior models (Giammarco et al, 2018).

Through scope-complete behavior modeling early in the lifecycle, when system architecture issues are less expensive to find and fix, this work provides Marine Corps Systems Command (MCSC) with a more comprehensive approach for exposing latent assumptions, constraints and requirements pertaining to their systems. Using MP automation for system architecture V&V results in the generation of more operational scenarios in less time, and with fewer errors, than can be achieved manually. This more comprehensive set of scenarios results in broader consideration of potential situations the actual system may encounter, and earlier identification of requirements necessary for mission success. More generally, this work demonstrates how MP is used to expose assumptions about an operation, derive logical and simplifying constraints from those assumptions (Quartuccio, 2019), and use those constraints to drive system requirements that may have otherwise been overlooked.

The scope-complete scenario generation capability of MP was used to explore the following research questions: 1) What are the alternative possible flows for a baseline mission, given events that can occur in the system's environment? 2) Can the mission scenarios be characterized with durations, probabilities and/or costs to support acquisition decisions?

Note: A limitation of this study is the availability of subject matter experts (SMEs) willing to volunteer their time in order to validate the model and its constraints. Therefore, the sample constraints applied to this model are only examples of constraints one might apply. Another limitation pertains to the assigning of probabilities to events; notional values were used in place of SME experiential or historical data.

Findings and Conclusions

The research methodology used the MP-Firebird tool for scope-complete scenario generation and characterization. To begin the research, we collected the source data (Department of the Navy, 2017) from the topic sponsor's delegate. A draft MP model was created for a baseline scenario from the information in these documents, and the operational content of the model was internally validated by a former Navy Lieutenant (now faculty associate-research) and by a former Marine. Once these SMEs were satisfied that we had a reasonable representation of a baseline scenario, we proceeded with modeling some alternatives to the baseline scenario that represented other "sunny day" cases as well as "rainy day" cases (off-nominal or failure scenarios). Our PhD student, John Quartuccio, contributed findings from his research on Bayesian belief networks for making probability calculations, as well as a pattern for object/sensor/processor/actor behaviors and interactions that applies to the MP model of littoral operations developed for this project.

Specifically, this research effort thoroughly explored our first research question, initially generating 105 alternative possible flows at scope 1 for a baseline littoral mission. The mission model formally captured the communication and decision flows for a Navy/Marine Expeditionary Ship Interdiction System platoon. Examples of alternatives include deployment or failure to deploy, platoon position remains concealed or exposed, and platoon is fully mission capable or partially mission capable. The MP model exhaustively generated all possible combinations of alternatives subject to event coordination constraints. After the application of systematically discovered logical and simplification constraints, 22 valid scenarios remained at scope 1.

Two important consequences of MP model structure are that 1) simple, implicit assumptions can be made explicit for all to understand and 2) assumptions coded as constraints can be toggled on or off to admit or reject different combinations of events during validation of the scenarios. These findings led to the conclusion that MP modeling supports requirements discovery and analysis by providing a high number of scenario combinations which cannot be achieved in a manual scenario generation process.

Our secondary research question explored the assignment of notional durations to key events to estimate whole scenario durations, as well as notional probabilities, for the key alternatives to calculate whole scenario probabilities. We verified a finding by systems engineering PhD student John Quartuccio that probabilities calculated by MP-Firebird do not account for zero-probability scenarios rejected by constraints (2019). This important contribution can be used to enable computation of Bayesian-based scenario probability estimates that account for scenarios purged by constraints, such as those identified in this project.

Recommendations for Further Research

MP-Firebird is a powerful tool for scenario generation that up to a user-defined scope of execution, is exhaustive. Our research has resulted in an MP model of littoral operations with a clear connection to a reusable pattern of interactions, exposed some tacit assumptions about the operation that may not have otherwise been formally recognized, and advanced our understanding of probabilities in scope-complete behavior models. Potential future work includes further testing of the MP modeling approach on a real system at MCSC to see if it can expose real requirements, while also working to quantify the value (e.g., in time or dollars) of having exposed the assumptions, constraints and need for requirements to an actual program office. A Naval Postgraduate School student working at MCSC would be an ideal candidate for involvement in this future work, as this relationship would help with the collection of source data for the actual system. Lastly, the completion of a standalone installation of MP software would facilitate running models of real systems in the MCSC work environment.

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MARINE CORPS WARFIGHTING LABORATORY (MCWL)

NPS-19-M117-A: Marine Corps Warfighting Laboratory (MCWL) Expeditionary Advance Base Operations (EABO) Wargaming

Researchers: Dr. Jeffrey Appleget COL USA Ret. and Mrs. Jane Barreto

Student Participation:

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Project Summary

For this project, through a program of wargaming and campaign analysis, the Marine Corps Warfighting Lab (MCWL) Naval Postgraduate School (NPS) faculty and students conducted research to advance the Expeditionary Advanced Base Operations (EABO) concept. Objectives of the wargames were to analyze US Marine Corps (USMC) and US Navy (USN) expeditionary capabilities, concepts for joint and coalition employment, and assess potential locations and logistics requirements for advanced expeditionary bases.

The following served as foundation for the design of events and conduct of this program of research: MCWL-NPS wargaming workshops, NPS student team-designed wargames from the OA4604 Wargaming Applications course, and NPS student team mini-studies from the OA4602 Joint Campaign Analysis. Our analysis identified technological and logistical gaps in current campaigns, and provides recommendations regarding communications and procedures across several USMC and USN joint operations.

Keywords: *wargaming, campaign analysis, Expeditionary Advanced Base Operations, EABO*

Background

As a newly developed concept, the Expeditionary Advanced Base Operations (EABO) seeks to further distribute lethality by providing land-based options to increase the number of sensors and shooters beyond the upper limits imposed by the available quantity of seagoing platforms. The EABO concept espouses employing mobile, relatively low-cost capabilities in austere, temporary locations forward as integral elements of fleet/Joint Forces Maritime Component Command operations. EABO may be employed to position Naval Intelligence Surveillance Reconnaissance assets, future coastal defense cruise missiles, anti-air missiles (to counter cruise and ballistic missiles as well as aircraft) and forward arming and refueling points, along with other expedient expeditionary operating sites for aircraft such as the F-35. Similarly, EABO can be employed to increase friendly sensor and shooter capacity while complicating adversary targeting by supporting critical munitions reloading teams for ships and submarines, or to provide expeditionary basing for surface screening/scouting platforms. These operations may also control, or at least outpost, key maritime terrain to improve the security of sea lines of communications and chokepoints, or deny their use to the enemy and exploit and enhance the natural barriers formed by island chains.

Findings and Conclusions

Concepts of Employment for Sea Control/Sea Denial (Marine Corps Warfighting Laboratory):

This wargame was used to determine effective concepts of employment for Naval Expeditionary Forces (NEF) to perform sea control and sea denial missions by securing (seizing or occupying), while establishing and sustaining bases that will employ joint sensors and shooters. Findings from this game are classified, and have been provided to MCWL.

MCWL Wargaming Workshop:

Analysis of this wargame focused on improving survivability and lethality of the force by the integration of NEF into the execution of Mine Counter Measure Operations' emerging doctrine and technology. The success of amphibious operations near-term (2025) relies on the development of Mobility, Counter-Mobility and Logistics operations concepts to support NEF. Our findings are based on a one-hour demonstration of this wargame. We concluded that the integration and utilization of new technology relies upon concise guidance from command, and likewise, command and control of units needs to be clear, with established communication requirements to ensure proper force integration.

Marine Corps Special Operations Command (MARSOC) Team 1 "Cold War 2020":

Our analysis of this wargame focused on phase zero or the "contact layer" in Indo-Pacific Command, Pakistan, and Afghanistan. The analysis is designed to determine the actions and partnerships MARSOC can enhance and develop to counter Chinese influence via the Belt and Road Initiative (BRI), while maintaining emphasis on countering violent extremist organizations. We determined that MARSOC should focus on South Korean and Mongolian partnerships, and also partnership efforts in India.

Additionally, MARSOC should conduct counterinsurgency, counterterrorism, and Foreign Internal Defense (FID) training in Pakistan, Sri Lanka, Thailand, Malaysia, and New Zealand, along with requesting intelligence sharing from certain countries to maintain situational awareness. In turn, we recommend maintaining MARSOC's current skill sets, and also developing a Civil Affairs (CA) or Military Information Support Operations (MISO) training for Marine Special Operations Teams, which can be deployed quickly to aid allied forces. In regards to increased missions, if MARSOC intends to expand the number of actions, they must also expand their personnel, while conducting a thorough analysis of the return on manpower investment for future missions. Lastly, MARSOC must understand how provocative actions will be viewed, and therefore utilize training with the highest return on investment, and with the greatest long-term benefit for partner nations.

MARSOC Team 2 "Secure the Victory":

In this renewed era of great power competition, MARSOC must work with and through joint, interagency, and coalition partners in the Philippines and the Philippines area of operations, in order to secure advantages in the "contact layer" while setting conditions to dominate in the "blunt layer." Our analysis of this wargame resulted in several recommendations. First, MARSOC/Special Operations Command Pacific (SOCPAC) should leverage placement and access in the Philippines through participation with maritime and joint training exercises, conferences, Humanitarian Assistance/Disaster Relief (HA/DR), joint information sharing regarding the Spratly Islands, counter-narcotics (CN), and representation in diplomatic engagements. Additionally, MARSOC/SOCPAC should leverage exercise-related construction requested by the Philippines for dual-purposed training and actual operations, such as helicopter landing zones, air strips, ports, boat houses, roads, warehouses, barracks, communications towers, and training facilities. Secondly, MARSOC/SOCPAC should increase engagement with Vietnam and Malaysia through CN, maritime and fisheries enforcement, anti-piracy operations, and other constabulary functions. Also, due to Vietnam's ties to China, Malaysia is more feasible as a future MARSOC partner, therefore SOCPAC requires an increased footprint to expand partnerships with Vietnam and Malaysia.

Additionally, MARSOC/SOCPAC should leverage civil action programs, Subject Matter Expertise Exchanges, mobile training teams, Naval Small Craft Instruction and Technical Training School, subsurface maritime training, key leader engagements and HA/DR. Likewise, SOCPAC should pursue efforts that mutually benefit interagency partners; for example, fisheries' efforts help USAID address environmental issues, enhances host nation capability, while providing an opportunity for SOCPAC to gain relationships, access, and maritime awareness. Therefore, it is imperative to advocate for more liaisons with Department of State, Drug Enforcement Agency, USAID, and other agencies. Similarly, it is necessary to streamline mutually supporting theater lines of effort across all organizations in the SCS. Specifically, leverage of SOF Liaison Officers could enhance lateral coordination and promote unity of effort in the SCS, while enhancing secure communications capabilities between MARSOC and Philippines forces, which would then significantly enhance real-time reporting and communication.

MARSOC Team 4 "Battle for Influence 2030":

Analysis of this wargame sought to answer the following questions: How can MARSOC prepare the environment for potential major combat operations in a South China Sea conflict scenario? In particular, how can MARSOC secure advantages in the "contact" layer while setting conditions to dominate in the "blunt" layer?

Our findings indicate that MARSOC should, first and foremost, increase influence in key areas of the Philippines. Missions that place MARSOC in the area of operations will set MARSOC up for success, including aerial and sea ports of debarkation, which are key for blunt layer operations.

MARSOC Team 5 (M-W) Team Chaos:

Our analysis looked at direct and indirect options for MARSOC and other SOF to apply pressure, and impose costs to deescalate or seize advantage in an escalation scenario in the Mekong River Watershed. These findings are classified and have been provided to MARSOC.

MARSOC Team 5 (T-Th) Special Operations in the South China Sea: Fight for Influence:

Wargame analysis was focused on SOF options in the contact-blunt layers to apply pressure and deescalate in a contested environment, e.g., the neighboring SCS nations of Taiwan, Philippines, and Vietnam. Our findings indicate that SOF actions employed in the contact layer support National Security policies and strategies: FID, Security Force Assistance, MISO, and CA. We observed that as the tensions between China and the US increase, SOF actions have shifted to more aggressive missions: unconventional warfare, Cyber, counterterrorism, direct action, strategic reconnaissance, and electronic warfare. Although no actions specifically deterred BRI, during the contact layer, SOF teams capitalized on messaging campaigns. During the blunt layer, the BRI infrastructure provided opportunity for exploitation by SOF teams and their partner forces both directly and indirectly, while messaging themes that highlighted the failure of BRI programs further enhanced exploitation. Additionally, capabilities across the contact and blunt layer spectrum can be increased by essential partnerships, and the permissions and authorities of non-traditional partner forces.

Recommendations for Further Research

Wargames and workshops provide valuable insights into USMC and USN expeditionary capabilities, joint and coalition capabilities to promote assessment of logistical requirements for expeditionary operations. Further operations research is required to better comprehend how the Marine Corps and Navy can interoperate more effectively to establish and maintain sea control in any maritime environment.

NPS-19-M271-A: MARSOC SOF-MAGTF Capabilities Integrations Analysis and Operational Modeling

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Student Participation: LCDR Sam Lehner USN, MAJ Robert Page USA, LT Jason Carminati USN, LT Brian Bird USNR, MAJ Jared Kassulke USA, MAJ Michael Culligan USA, Maj Tyler Oldham USAF, and Maj Daniel Gipper USAF

Project Summary

This research, leveraging the NPS Warfare Innovation Continuum (WIC) and working in conjunction with ongoing Naval Postgraduate School (NPS) and Marine Corps Warfighting Laboratory efforts examining Expeditionary Advance Base Operations (EABO), analyzed Special Operations Forces - Marine Air-Ground Task Force (SOF-MAGTF) capabilities integrations in a future Distributed Maritime Operations (DMO).

This effort focused on exploring, assessing and identifying SOF-MAGTF capabilities integrations to improve current and future EABO operations. 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 Special Operations Forces (SOF) and deployed MAGTFs, to maximize the complementary capabilities of each formation. This research 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, we examined MARSOC, United States Marine Corps (USMC), and United States Navy (USN) cooperative missions in the South China Sea through wargaming and analysis studies. Our 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: *wargaming, campaign analysis, Expeditionary Advanced Base Operations, EABO, MAGTF*

Background

EABO 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. Essentially, 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, and are able to respond immediately to crises, as well as perform operations in a sustained campaign.

The wargames utilized in our 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, that 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.

Findings and Conclusions

Our efforts resulted in findings and recommendations for each of the issues below:

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 actions can and should MAGTF take to capitalize on identified opportunities?
4. What indirect approaches in the Contact Layer could provide opportunities and advantages in the Blunt Layer and deter major conventional war?
5. What AFP partners are most effective and efficient for mission accomplishment?

6. What is the Contact Layer's risk assessment of indirect approaches/actions by MARSOC?

Issue 1: The Marine Special Operation Company (MSOC) is well postured to conduct Operational Preparation of the Environment and to provide reception, staging, and onward integration assessments of infrastructure/adaptive basing. MSOCs should become well-versed in Theater Special Operation Command strategic and operational plans, and Department of State (DOS) Integrated Country Strategy for the Philippines and EDCA, during the inter-deployment training cycle (IDTC).

Additionally, per MARSOF 2030 (MARSOC 2018), MARSOC Leadership should attempt to attend the 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, Pacific, and United States Indo-Pacific Command. This approach enables a larger return on strategic, operational, and tactical investments, and ties these efforts with larger/long-term interagency and whole-of-United States Government strategy and nests efforts with AFP plans and initiatives.

Issue 2: SOCPAC entities, 31st MEU, and the SEVENTHFLT are not properly synchronizing Operations, Actions, and Activities (OAAs) during the IDTC or on deployment. Increased collaboration and future 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 for execution on deployment by the rotational MSOC.

Issue 3: There is a need for increased command, control, communication, and intelligence with MARSOC during IDTCs and on deployments. To address this issue, we recommend 31st MEU personnel participate in MARSOC IDTC, validation of the 31st MEU SOFLE requirement, leveraging Joint Chief of Staff exercises 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, and 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 between, 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, increasing MAGTF capability and capacity will improve price, availability, and influence to Conventional AFP Joint Task Force Commanders 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; 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 greatly increase warfighting readiness compared to small exercises, they increase the vulnerability of collection by adversaries due to large operating footprints. 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 DMO and EABO are two nascent concepts that will require further operations research in order to better understand how the USMC and the USN can use them to interoperate more effectively, in order 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, in order to best serve the U.S. Department of Defense.

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NPS-19-M285-A: Using Virtual Environments to assess Human-Robot Teams during MAGTF Operations

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Student Participation: LtCol Tobias Brennenstuhl USMC, Maj Bert Knobloch USMC, Maj Daniel Yurkovich USMC, Capt Thomas Schutt USMC, Capt Lauren McCann USMC, Capt Jon Boron USMC, and Capt Colton Federoff

Project Summary

With the emergence of robots on the battlefield, it is critical for the Marine Corps to tactically integrate existing unmanned assets with manned systems during Marine Air Ground Task Force (MAGTF) operations. In parallel, the Marine Corps must also look forward to identify capability gaps that future unmanned systems might address. To do both requires extensive field testing, which is often unfeasible and always costly. This effort proposes the use of virtual environments (VE), virtual reality (VR) and agent-based modeling to conduct scenario-based assessments of Manned-Unmanned Teaming (MUM-T) during combat operations.

To pursue such goals, the project examined a variety of relevant tactical scenarios where Marines and robots act in concert to achieve specific mission objectives. Such tactical scenarios are further assessed using deterministic combat simulations to create a valid methodology for behavior creation and assessment within each scenario-specific problem space. Support for a complete range of combat simulations was determined as a necessary part of VE design explorations since specific MUM-T tactics, techniques and procedures (TTPs) are expected to co-evolve constantly as sensor, communication, and vehicle capabilities continue to improve.

Such diversity was supported through establishment of the Naval Postgraduate School (NPS) Modeling Virtual Environments and Simulation (MOVES) Live Virtual Constructive (LVC) Laboratory for diverse simulation tools. Additionally, two general approaches for the coordination of Manned Unmanned Teaming (MUM-T) behaviors were considered, each beginning with a high-level description of expected behaviors; completion of the goal tasks indicates that combined human-robot teams have achieved a desired world state.

Keywords: *virtual environments, VE, virtual reality, VR, extensible three-dimensional, X3D graphics, SPIDERS3D, Institute for Electrical and Electronic Engineers, IEEE, Distributed Interactive Simulation, DIS, Live Virtual Constructive, LVC*

Background

This research surveyed a large variety of combat models and visualization tools to create the best and broadest possible environment for Marine Corps decision-makers to understand the complexity and warfighting value of the Manned-Unmanned Teaming (MUM-T) battlespace. Shared VEs can potentially be used during force-development efforts to plan for the integration of MUM-T into combat units. As the Department of Defense (DoD) is generally unfamiliar with such operations, but is eagerly anticipating their development, it is quite clear that the use of live, virtual, constructive LVC simulations to wargame these capabilities becomes fundamental for all progress. Ultimately, such MUM-T co-development is the critical path needed to expand MAGTF capabilities and avoid MAGTF vulnerabilities.

The use of virtual environments for unmanned systems combines two of the biggest areas of research activity in the DoD; applying them to MUM-T places such work at the highest priority of 21st-century military challenges. Therefore, the use of LVC simulations to wargame these capabilities is fundamental. In parallel, the Marine Corps must identify the capability gaps of future unmanned systems. Our efforts have worked to achieve generality, scalability, and functionality in all respects in order to meet such challenges.

Findings and Conclusions

This work examined a variety of relevant tactical scenarios where Marines and robots act in concert to achieve specific mission objectives. Such tactical scenarios were further assessed using deterministic combat simulations in order to create a valid methodology for behavior creation and assessment within each scenario-specific problem space. Support for a complete range of combat simulations was determined as a necessary part of VE design explorations, since specific MUM-T tactics, techniques, and procedures (TTPs) are expected to co-evolve constantly as sensor, communication, and vehicle capabilities improve. These diverse simulation tools were supported through the MOVES LVC Laboratory at the Naval Postgraduate School. Additionally, two general approaches for the coordination of MUM-T behaviors were considered, each beginning with a high-level description of expected behaviors; completion of the goal tasks indicates that combined human-robot teams have achieved a desired world state. While Marines teaming with machines provide an essential margin on the battlefield, success will be determined by human effectiveness to harness and lead such teams.

Understanding of these capabilities will grow through rehearsal and testing in virtual environments, as a massive set of capabilities is emerging in these domains. Our diverse and integrative work on Institute for Electrical and Electronic Engineers Distributed Interactive Simulation (DIS) Protocol, Extensible 3D (X3D) Graphics International Standard, and the SPIDERS3D Virtual Environment, indicate that general

solutions to this important challenge are possible. Additionally, the use of open standards (DIS, X3D) and open source (SPIDERS3D), means that diverse systems, models, streams, and repeatable “lessons learned” can continue to grow more broadly and deeply.

Recommendations for Further Research

In order for warfighters to fully understand the capabilities, limitations, risks, and progress of this technology, virtual environments that integrate field experimentation, and modeling and simulation data streams using 3D models for visualization, should be used within a shared collaborative network. Interoperable Web standards ensure that specialty systems can bridge together compatibility, rather than languishing as unusable disconnected blocks of isolated functionality; prototype work in this project shows great potential for broad and repeatable solutions to these critical problems. All future work should be grounded by LVC interoperability testing, to ensure that global progress can continue, avoiding the “stovepipe” constraints that limit many current approaches.

NPS-19-M286-A: Designing and Provisioning for a Consistent C2 Approach for Marine-Machine Teaming

Researchers: CAPT Scot Miller USN Ret. and Dr. Dan Boger

Student Participation: Capt Mike Franco USMC and Capt Steve Spada USMC

Project Summary

This research aimed to develop a framework that facilitates human machine teaming (HMT) between unmanned technologies and the Marines using them. Designed to promote the best attributes of both Marines and unmanned systems (UxS) in operations, HMT is a new area of research in the military. The researchers conducted a thorough literature review that expanded on command and control (C2) fundamentals and myths of automation, cognitive load, interdependence, doctrinal concepts from the Marine Operating Concept, and the Knowledge Value Added (KVA) approach. This analysis formed the backbone of the research and provided the foundation for a C2 HMT framework. The framework provides a pre-operations checklist for using UxS so that Marine HMT is effective in the next era of warfare.

Keywords: *artificial intelligence, AI, command and control, C2, human machine teaming, HMT, interdependence analysis, IA, mesh network, tablet, unmanned systems, UxS*

Background

The words innovation, autonomy, and artificial intelligence are thrown about with regularity in the Department of Defense (DoD) and in the private sector. This research hypothesized that those terms are not neatly packaged, nor are definitions roundly agreed upon, therefore, a framework or checklist for using robots in Marine Corps operations is needed. We found that the future of semi-autonomous and autonomous assets is dependent on the continued research into HMT. Designers and developers of HMT technology must understand the premise of interdependence (Johnson, 2014). Interdependence analysis determines the best ways for humans and machines to team, and makes it a focal point of the design process for UxS.

Humans should and will remain a part of the UxS design for the foreseeable future not only because of the limited capabilities of the machines, but also because humans and machines working as a team are more effective than either working individually.

Findings and Conclusions

The research concluded USMC doctrine and concepts must match an anticipated future where units are spread out across the battlespace. The fifth epoch of warfare will look nothing like the fourth—just as the fourth looked nothing like the third. The era of warfare the U.S. is about to enter will likely feature small units operating independent of their larger parent element, and because UxS are available to assist, conducting missions that were once reserved for battalions and regiments (Scales, 2018).

The DoD must continue to adopt mobile ad hoc networking technology such as TrellisWare, that facilitates C2 across the battlespace and allows small unit leaders to operate independent from higher command elements. In addition, the Marine Corps must continue to refine their C2 approach to one that truly allows for decentralized decision-making. This is needed to permit small units to utilize the full capabilities of the systems at their disposal, without requiring continuous reach back to higher command echelons. The C2 HMT framework presented is a simple but powerful tool to help small-unit leaders effectively employ the new battlefield technology, especially UxS.

A second finding is that the DoD should analyze new capabilities through a value-added approach, not a cost-savings mindset. The rapid advancement of technology has placed a plethora of highly capable systems in the purview of DoD decision makers. However, many of these systems have been developed with a focus on maximizing systems capabilities instead of filling needs of tactical units. At times this can lead decision makers to the fallacy of a replacement mindset, as opposed to a value-added mindset. The decision tree of replacement technologies drives analysts to take a cost cutting and savings stance, in order to produce a strong return on investment. However, the KVA analysis shows that technology should be analyzed through the value it adds to the warfighter (Housel & Bell, 2001). This value can come in the form of increasing time efficiencies and process throughputs, instead of decreasing expenses. Return on knowledge is not simply a way of putting positive spin on spending substantial money; it is a way to analyze processes through what is actually accomplished, as opposed to only focusing on costs saved or expenses incurred.

Recommendations for Further Research

Numerous articles have been written about the Marine Corps' future and what role it will likely perform in future conflicts. Whether countering littoral actions by great power adversaries or performing traditional mission sets such as a movement to contact, further application of this C2 HMT framework to complex scenarios is recommended. Expanding the framework to future modes of Marine Corps' warfare will make the framework ever more useful. Furthermore, as technologies such as mobile ad hoc networking, situation awareness tablets, and modular multi-mission UxS are adopted, the tactics, techniques, and procedures of the Marines with this gear should be analyzed. Matching the realistic use of the gear with the Marine Corps mission sets will facilitate the learning process for both the Marines and the machine designers. The C2 HMT framework helps in adapting new ways of operating, but actual investigation should continue regarding new tactics, technologies, and environments.

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LIST OF ABBREVIATIONS AND ACRONYMS

3D - three-dimensional	BER - Bit error rate
A2/AD - anti-access and area denial	BIT - built-in-test
AAR - after-action report	BLOS - Beyond Line of Sight
ABS - acrylonitrile butadiene styrene	BLT - Battle Load Tool
ACS - Adaptive Cycle State	BMA - Battle Management Aid
ADF - Australian Defence Force	BRI - Belt and Road Initiative
ADRAM - Airframe Depot Readiness Assessment Model	BUNO - bureau number
ADS-B - Automatic Dependent Surveillance-Broadcast	C2 - command and control
AEM - Adobe Experience Manger	C5I - Command, Control, Communications, Computers, Collaboration, and Intelligence
AFP - Adaptive Force Package	CA - Civil Affairs
AFP - Armed Forces of the Philippines	CAN - Controller Area Network
AHP - Analytical Hierarchy Process	CASoS - Complex Adaptive Systems of Systems
AI - artificial intelligence	CBA - Cost Benefit Analysis
AIS - Automatic Information System	CCM - Combat Craft Medium
AM - additive manufacturing	CDET - College of Distance Education and Training
AMSAA - Army Material Systems Analysis Activity	CDEW - Counter Directed-Energy Warfare
AoA - Analysis of Alternatives	CDI - collateral duty inspector
AOR - area of responsibility	CDQAR - collateral duty quality assurance representative
AP - as-printed	CEUs - continuous education units
APEX - Application Express	CF - carbon fiber
AR - Augmented Reality	CFG - constant frequency generator
ARMM - Autonomous Region of Muslim Mindanao	CID - Combat identification
ARSENL - Advanced Robotic Systems Engineering Laboratory	CIS - communication and information systems
ARSST - Army Space Support Team	CIV - civilian
AS - Autonomous Systems	CIVINT - civilian intern
ASEAN - Association of Southeast Asian Nations	CL - continuous learning
ASIAEX - Asian Seas International Acoustics Experiment	CLF - Combat Logistics Force
ASTC - Aviation Survival Training Center	CLO - Combat Logistic Officer
ASW - Anti-submarine warfare	CMS - content management system
ATC - action taken code	CMS - Containerized Missile System
AVDLR - aviation depot-level repairable	CN - Counter Narcotics
AWF - acquisitions workforce	CNC - computer numerical control
BDA - big data analytics	CNO - Chief of Naval Operations
BEMOS - Bayesian ensemble model output statistics	CNSF - Commander, Naval Surface Forces
	COA - Course of Action
	COC - Combat Operations Center
	COI - community of interest
	COMSUBPAC - Commander, Submarine Force, U.S. Pacific Fleet

LIST OF ABBREVIATIONS AND ACRONYMS CONT.

COP - Common Operational Picture	DRM - dynamic retention model
COP - community of practice	DSTG - Australian Defence Science and Technology Group
COR - Contracting Officer Representative	E4S - Education for Seapower
COT - Customer ordering tracking	EA - Electronic Attack
COTF - Commander, Naval Operational and Test Force	EABO - Expeditionary Advanced Base Operations
COTS - civilian off the shelf	EBS - e-business suite
COTS - commercial off the shelf	ECU - electronic control unit
CPSoS - cyber physical system of systems	EDA - exploratory data analysis
CRISP-DM - cross industry standard process for data mining	EDCA - Enhanced Defense Cooperation Agreement
CS - Computer Science	E-DOSPERS - Engineering-DOSPERS
CT - counter terrorist	EDRAM - Aviation Engine Depot Readiness Assessment Model
CTAP - Common Tactical Air Picture	EDRAM - Engine Depot Readiness Assessment Model
CWC - Composite Warfare Commander	EDS - Energy Dispersion Spectroscopy
CWT - customer wait time	EMCON - Emissions Control
DANTE - Directional Ad Hoc Networking Technology	EMO - Enhanced MAGTF Operations
DARPA - Defense Advanced Research Projects Agency	EO/IR - surface electro-optic infrared sensors
DASN - Deputy Assistant Secretary of the Navy	ESM - Electronic Support Measures
DB - Database	E-VUCA - volatile, uncertain, complex and exponentially accelerating
DBSCAN - Density Based Spatial Clustering of Applications with Noise	ExMCM - Expeditionary Mine Counter Measures
DDG - Guided Missile Destroyer	FEC - Forward error correction
DE - Directed Energy	FEM - Finite Element Method
DEA - data envelopment analysis	FHP - Flight Hour Program
DEA - Drug Enforcement Agency	FID - Foreign Internal Defense
DED - directed energy deposition	FINN - Fused Integrated Naval Network
DEW - Directed-Energy Weapon	FITREP - Fitness Report
DL - deep learning	FoI - frequency of inspection
DL - Distributed Lethality	FRC - Fleet Readiness Center
DLA - Defense Logistics Agency	FSO - Free space optical
D-level - depot-level	FSP - Floating Shock Platform
DMO - Distributed Maritime Operations	FSST - Full Ship Shock Trial
DoD - Department of Defense	FTE/FTEs - Flight Training Event/Events
DOE - design of experiments	FYDP - Future Years Defense Plan
DON - Department of Navy	GCLT - Generalized Central Limit Theorem
DON - Department of the Navy	GCSS-MC - Global Combat Support System-Marine Corps
DOS - Department of State	GDF - Guyana Defence Force
DOSPERS - Domain-Specific Risk-Taking	GenOC - Generalized Optimal Control
DOTMLPF - Doctrine, organization, training, material, leadership, personnel, and facilities	
DRAM - Depot Readiness Assessment Model	

LIST OF ABBREVIATIONS AND ACRONYMS CONT.

GT - game theory	KO - Contracting Officer
GY - German Army	KR - Knowledge Representation
HA/DR - Humanitarian Assistance/Disaster Relief	KS - Kolmogorov-Smirnov
HDFS - Hadoop Distributed File System	KSAs - Knowledge, Skills, and Abilities
HEL - High-Energy Laser	KVA - knowledge value added
HIP - Hot Isostatic Pressing	LAILOW - leverage AI to learn, optimize and win
HMT - human-machine teaming	LCM - Logistics Chain Management
HPM - High-Power Microwave	LCS - Littoral Combat Ship
HPRF - High-Power Radio Frequency	LFT&E - Live Fire Test & Evaluation
HPT - high performing team	LG - Linguistic Geometry
HQ - headquarters	LITMUS - Lightweight Interstitials Toolkit for Mission Engineering Using Simulation
HSP - Husbandry Service Provider	LLA - Lexical Link Analysis
HT - heated treated	LLP - lessons learned program
HT - heat-treated	LMACC - lightly manned autonomous combat capability
HVP - Hyper-Velocity Projectile	LMS - Learning Management System
ICC - Information Coordination Center	LOS - Line of Sight
IDTC - inter-deployment training cycles	LPD - low probability of detection
IE - Information Environment	LPI - low probability of interception
IFDL - Intra-Flight Data Link	LRF - Long range forecasts
IID - independent, identically-distributed	LSV - Logistics Support Vehicle
I-level - intermediate-level	LVC - Live Virtual Constructive
INDOPACOM - Indo-Pacific Command	M&S - Modeling and simulation
INF - Intermediate-Range Nuclear Forces Treaty	MAC - Multiple Award Contract
IO - information operations	MADL - Multi-functional Advanced Data Link
IP - Internet Protocol	MAGTF - Marine Air-Ground Task Force
IR - Infrared	MAL - malfunction code
IRB - Institutional Review Board	M-AM - Metal Additive Manufacturing
IS - Information Systems	MANET - mobile ad-hoc network
ISR - Intelligence, Surveillance, and Reconnaissance	MARFORPAC - Marine Corps Forces, Pacific
IT - Information Technology	MARFORPAC - Marine Forces, Pacific
JDTA - Job/duty task analysis	MARSOC - Marine Corps Forces Special Operations Command
JF - Joint Fires	MARSOC - Marine Forces Special Operations Command
JFMCC - Joint Force Maritime Component Commander	MBSE - Model Based Systems Engineering
JIATFSouth - Joint Interagency Task Force South	MC - mission capable
JNLWD - Joint Non-Lethal Weapons Directorate	MCDA - multi-criteria decision analysis
JTF - Joint Task Force	MCM - Mine Countermeasures
KB - Knowledge Base	MCR - Message Completion Rate
KFT - Knowledge Flow Theory	MCS - Monte Carlo simulation
KM - knowledge management	MCSC - Marine Corps Systems Command

LIST OF ABBREVIATIONS AND ACRONYMS CONT.

MCWL - Marine Corps Warfighting Lab	NETC - Naval Education and Training Command
MDOF - Multi-degree of Freedom	NETC - Navy Education and Training Command
MDUSV - Medium Displacement Unmanned Surface Vehicle	NFO - naval flight officer
MEB - Marine Expeditionary Brigade	NFR - non-functional requirement
MEF - Marine Expeditionary Force	NHT - Normobaric Hypoxia Training
MEF-MIG - Marine Expeditionary Force Information Group	NIR - Near-Infrared
MEMS - Microelectromechanical Systems	NISE - Naval Innovation in Science and Engineering
MEU - Marine Expeditionary Unit	NIST - National Institute of Standards and Technology
MIG - MEF Information Group	NLIW - Nonlinear internal wave
MILDEC - military deception	NLLP - Naval Lessons Learned Program
MIMO - multiple input/multiple output	NLW - Non-Lethal Weapon
MISO - Military Information Support Operations	NoSQL - Not only SQL
ML - machine learning	NPS - Naval Postgraduate School
MMCO - Material Maintenance Control Officer	NR&DE - Naval Research and Development Establishment
MOE - measure of effectiveness	NRC - Navy Recruiting Command
MOS - military occupational specialty	NRP - Naval Research Program
MOS - Model output statistics	NSF - National Science Foundation
MOVES - Modeling, Virtual Environments, and Simulation	NSS - Navigation, Seamanship, and Ship-handling
MP - Mission planning	NSWC - Naval Special Warfare Command
MP - Monterey Phoenix	NWC - Naval War College
MPE - mission partner environment	NWDC - Naval Warfare Development Command
MRO - maintenance, repair, and overhaul	NWP - Numerical weather prediction
MSOC - Marine Special Operation Company	O&M - operations and maintenance cost
MSST - Marine Space Support Team	OIE - Operations in the Information Environment
MST - Marine Sonic Technology	OJT - on the job training
MSTIFF - Marine Sonar Technology Image File Format	O-level - organizational-level
MUM-T - Manned-Unmanned Teaming	OOA - operations, actions, and activities
MUNIN - Maritime Unmanned Navigation through Intelligence in Networks	OOD - Officer of the Deck
NA - Nigerian Army	OODA - Observe-Orient-Decide-Act
NAS - Naval Air Station	OPNAVN81 - Chief of Naval Operations, Assessment Division
NASTP - Naval Aviation Survival Training Program	OPSEC - Operational Security
NATO - North Atlantic Treaty Organization	OTH-T - Over-the-horizon targeting
NAVAIR - Naval Air Systems Command	OTTER - Optimized Transit Tool & Easy Reference
NAVSEA - Naval Sea Systems Command	P/PM - Performance/Pricing Model
NAVSUP - Naval Supply Systems Command	
NDN - Named Data Networking	
NEF - Naval Expeditionary Forces	

LIST OF ABBREVIATIONS AND ACRONYMS CONT.

PA - Predictive Analytics	RPM - revolutions per minute
PATT - Planning and Advisory Training Team	RRL - Ready, Relevant, Learning
PBF - powder bed fusion	RSLF - Royal Saudi Land Forces
PETG - glycol modified polyethylene terephthalate	SA - Situation Awareness
PI - principle investigator	SAR - search and rescue
PIM - Plan of Intended Movement	SATCOM - Satellite Communications
PIMC - Philippine Marine Corps	SC - supply chain
PKI - Public Key Infrastructure	SCS - South China Sea
PLA - polylactic acid	SE - Systems Engineering
PLI - position/location/information	SEM - Scanning Electron Microscopy
PMOS - primary military occupation	SES - Senior Executive Service
PoF - Physics of Failure	SEVENTHFLT - United States Seventh Fleet
POL - patterns of life	SF - Security Force
POM - Program Objective Memorandum	SFARP - Strike Fighter Advanced Readiness Program
PPBE - Planning, programming, budgeting, and execution	SFG - secure file gateway
PQS - personnel qualification standards	SGF - Slovak Ground Forces
PSYOPs - psychological operations	SIG - Social Identity Group
QAR - quality assurance representative	SIGINT - signals intelligence
QDA - Qualitative Data Analysis	SISO - Single input/single output
QR - Quick Response	SME - Subject Matter Expert
R&D - research and development	SMU - Supply Management Unit
RAS - replenishment at sea	SNA - social network analysis
RAT - Readiness and Availability Tool	SNR - Signal to noise ratio
RDTE - research, development, test and evaluation	Soar-RL - Soar reinforcement learning
RE - Running Estimate	SOCAPAC - Special Operations Command-Pacific
RES - Reduction Expansion Synthesis	SOF - Special Operations Forces
RES-SM - Reduction Expansion Synthesis-Sintered Metal	SOFLE - Special Operations Forces Liaison Element
RF - Radio Frequency	SPAWAR - Space and Naval Warfare Systems Command
RGB - red-green-blue	SPMAGTF - Special Purpose Marine Air Ground Task Force
RI - random index	SQL - Structured Query Language
RL - reinforcement learning	SRB - Selective Reenlistment Bonus
RNCOM - Regional Navy Ocean Coastal Model	SRB - Selective Retention Bonus
RO - reorder point	SSE - systems security engineering
ROCN - Republic of China Navy	ST - strategic thinking
ROE - rules of engagement	ST-COI - Strategic Thinking Community of Interest
ROI - return on investment	STEM - science, technology, math and engineering
ROK - return on knowledge	STS - Sociotechnical System
ROKA - Republic of Korea Army	
ROP - reorder up-to point	
RoR - Rules of the Road	

LIST OF ABBREVIATIONS AND ACRONYMS CONT.

SURFDEVRON - Surface Development Squadron
SWO - Surface Warfare Officer
SWOS - Surface Warfare Officer School
TALONS - Towed Airborne Lift of Naval Systems
TAN - tactical airborne network
TASP - Teams of Autonomous Systems and People
TCP - transmission control protocol
TERA - Temporary Early Retirement Authority
TF - task force
TIFF - Tagged Image File Format
TOC - total ownership cost
TTP - tactics, techniques and procedures
UAS - Unmanned Aerial System
UAV - Unmanned Aerial Vehicles
UC - use-case
UI - under instruction
ULSV - unmanned logistics surface vehicle
UNDEX - Underwater Explosions

USCG - United States Coast Guard
USMC - United States Marine Corps
USN - United States Navy
UUV - Unmanned Underwater Vehicle
UWB - ultra wideband
UxS - unmanned system
V&V - verification and validation
VE - virtual environments
VR - virtual reality
VSP - Voluntary Separation Pay
VUCA - volatile, uncertain, complex and ambiguous
WIC - Warfare Innovation Continuum
WMN - wireless mesh network
WRENCH - Workbench for refining Rules of Engagement against Crowd Hostiles
X3D - Extensible 3D (X3D) Graphics International Standard
xAPI - Experience API
XRD - X-ray Diffraction



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