Fiscal Year 2022 Annual Report

NAVAL RESEARCH PROGRAM

NAVAL POSTGRADUATE SCHOOL

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NPS IN SUPPORT OF NAVAL CONCEPT & CAPABILITY DEVELOPMENT AND DECISION MAKING

Naval Postgraduate School (NPS) Naval Research Program (NRP) studies sponsored within FY22 have made significant contributions to the Department of the Navy by providing insights to key operational problems that decision-makers face, along with recommendations to support cost savings in a fiscally constrained environment. The NRP's program goals and execution support the Chief of Naval Operations' vision of NPS as the Navy's applied research university. The interactions, experiences and knowledge gains that occur here are unique; it would be difficult to replicate them anywhere else in the world, which makes NPS an invaluable Fleet asset.

This report highlights results from the spectrum of NRP research activities conducted on behalf of both Navy and Marine Corps Topic Sponsors during the 2022 fiscal year. Executive summaries from the research projects are included in the report. While most of those summaries detail final results and recommendations for further research, some projects have multi-year project lengths. In those cases, progress-to-date is reported.

The 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.

Finally, the many benefits that accrue through the NRP depend on the wholehearted participation of NPS faculty, students, and the many Topic Sponsors from across Navy and Marine Corps headquarters commands. NRP extends thanks to all who have participated this year and since the program's inception in 2014.

Sincerely,

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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 (CNO) and supports research projects for Navy and Marine Corps. The NPS NRP serves as a launch point for the new initiative 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.

NRP is a U.S. Navy program of record (POR) resourced at between $11M and $14M annually. The NRP POR is officially titled "Naval Postgraduate School (NPS) Studies Support: Faculty and Student Studies, Analysis and Research."

NPS research and analysis activities serve as a focal point, stimulus, and major source of strategic, tactical, and operational thought within the Navy communities. These efforts generate strategic and operational alternatives, tactical imperatives, quantitative analyses, technical developments and assessments, and political-military assessments. They also provide recommendations to the CNO, Fleet Commanders and numbered Fleet Commanders regarding the formulation and execution of maritime options for the President of the United States. Research will be conducted to support graduate students' theses determination and completion as part of Faculty projects. These research activities also serve as a means for OPNAV Resource Sponsors and Major Commands to have analysis and decision support research conducted in the uses of the applied, soft, and hard sciences in solving diverse and complex resource allocation and strategic issues facing the Navy today and envisioned in the future.

NPS administers the NRP to provide relevant thesis and capstone project opportunities for NPS students; to provide operational awareness for NPS faculty; and to contribute to problem solving and increased capabilities across the naval service. Organizationally, NRP is part of the Naval Warfare Studies Institute. OPNAV N80 is NRP's Budget Submitting Office. NRP is funded entirely as Budget Activity 6.6 (RDT&E Management Support).

Since its inception, NRP has funded a large number of NPS Principal Investigator (PI)-led studies each year with an average cost ranging from $75–175K. The vast majority of NRP funding pays faculty members' salary with a smaller amount for travel or other direct expenses. The vast majority of NRP projects are UNCLASSIFIED. Deliverables range from a poster to 100+ page technical reports depending on individual topic advocates' requirements. NRP topics are almost universally related to concept or capability development. However, due to the restrictions of BA RDT&E 6.6 funding, research is limited to "studies and analyses in support of the RDT&E program."

ASN(RDA) - Research, Development, and Acquisition

NPS-22-N033-A: Utilizing Virtual and Augmented Reality to Augment Real World Operational Training to Improve Proficiency

Researcher(s): Amela Sadagic, and Douglas Van Bossuyt

Student Participation: LT Steven Arnold USN

Project Summary

Recent years have been marked by the emergence of affordable off-the-shelf solutions in Virtual Reality (VR) and Augmented Reality (AR) technology. Those advances created a unique opportunity for exercising transformational approaches to personalized, just-in-time relevant training of large numbers of people. The research studies suggest that the systemic application of novel technical solutions in training will have a major positive impact on operational readiness regardless of community size or Department of Defense (DoD) service demographic. These results are especially relevant during times of financial constraints, or environmental limitations such as pandemics.

We executed a series of research activities to identify best-in-class contemporary VR/AR training solutions used by the U.S. Navy (USN) and map those systems' capabilities to the U.S. Coast Guard's (USCG) needs. Our findings suggest that the most prevalent computer-supported training solutions in both the USN and United States Marine Corps (USMC) are in the class of training simulators; examples include simulators for ship navigation, convoy courses, marksmanship, and flight simulators. They are typically connected with well-structured curricula, and their use is mandated; over time, they became an integral part of the training regimen in both services. Good examples of places where they are deployed are schoolhouses and simulation centers that maintain those simulators and schedule regular training. Training systems that use VR and AR technology are predominantly on the level of prototypes, used locally (not widespread across services), and typically provided as an option to the training force.

In addition to a survey of current training solutions, we conducted technology market research, identified representative technological solutions, and reviewed their capabilities. We illustrated the best use cases and produced a set of recommendations on selecting training systems that match trainees' needs. In addition to VR and AR training solutions, we identified several other candidate technologies and training

approaches that hold promise in addressing the United States Coast Guard's (USCG) training needs and produced a set of recommendations on how to select, promote and use training solutions to increase the probability of those systems being adopted and used by the trainees.

Keywords: *training, virtual reality, VR, augmented reality, AR, human performance, large scale adoption of technology, training effectiveness*

Background

The most recent wave of affordable, commercial off-the-shelf (COTS) hardware and software solutions has already generated great benefits in many domains. Scores of VR and AR head-mounted displays (HMDs), also called heads-up displays, with reasonably good display resolution, a field of view (FOV), image quality, and head tracking as well as easy-to-use yet powerful 3D game engines have created a renewed interest in VR and AR domains and applications. Their technological performance, robustness, and low cost made them a great contender as a training solution of choice when addressing the needs of a large number of potential users; they have raised the hopes and interests of stakeholders in many domains, including the DoD. Together with optimized interfaces and pedagogies, those solutions create a unique opportunity for exercising transformational approaches to personalized, just-in-time relevant training of large numbers of people. Systemic application of those systems in operations and training would have a significant impact on operational readiness. These results are especially relevant during times of financial constraints or environmental limitations such as pandemics.

The efforts to leverage the potential and power of those training systems to address the needs of the USN started a while ago; as a result, the service created a good set of solutions that supports its training needs. In the project, we conducted a series of research activities to identify best-in-class contemporary VR/AR training solutions used by the USN and USMC, and mapped those systems' capabilities to the USCG needs. Although the research questions addressed in this effort are focused on current USN training solutions and practices, there is sufficient evidence to support the transferability of training effectiveness across services, resulting in a tenfold return on taxpayer investment. Further, this VR/AR research complements congressionally mandated interoperability requirements for USN and USCG while simultaneously addressing USCG training gaps/shortfalls.

An additional component of the project work consisted of highlighting the domains and areas where neither USN nor USCG has technology-supported VR/AR training solutions. To fully address the latter, we used our knowledge of USN and USCG missions and training needs and our expertise in novel technologies and capabilities of their sensory modalities and produce advice on addressing those needs with novel solutions. Our overarching goal was to provide both leadership and practitioners with the necessary tools and guidance to help them navigate the landscape of novel training systems and select the best option given their requirements, needs, and constraints.

This research produced a master's student thesis; the text includes a manuscript that will be submitted for publication in a professional journal.

Findings and Conclusions

Our initial plan was to focus only on VR and AR training solutions; however, it became apparent that we would need to include training simulators in our survey. Frequent examples of this type of training solution include simulators for ship navigation, convoy courses, marksmanship, and flight simulators. These are characterized by a range of visual displays and the physical mock-up of the panels with instruments and the seat for the operators; in some cases, they include physical simulation of the entire room within which a group of operators is expected to work.

Our findings suggest that the most prevalent computer-supported training solutions in both USN and USMC are in the class of training simulators. They represent capital investments on the part of each service, and they have been established as alternatives to costly training in the real-world environment; the reduction of the costs and flexibility they afford to the training force have been the main reasons for their introduction. The same solutions are typically supported with well-structured curricula, and their use is mandated; over time, they became an integral part of the training regimen in both services. In some cases, they represent the only training option available to trainees (flight simulators are in that category), and in other cases, they are used as a means to increase trainees' skill level in case they did not achieve performance standard measured after traditional training approaches (marksmanship trainer Indoor Simulated Marksmanship Trainer is used that way). Good examples of places where they are deployed are schoolhouses and simulation centers that maintain those simulators and schedule regular training. They are funded each year, and in that sense, they represent stable and reliable training solutions.

We also found that in contrast to simulators, training systems that use VR and AR technology are predominantly on the level of prototypes, used locally (not widespread across any service), and typically provided as an option to the training force. Their longevity has been lacking; the systems that we have been familiar with through our prior work in the training domain no longer exist. We also found that the current number of VR and AR solutions in USN and USMC is remarkably low. It is also possible that introduction of those training solutions was not done properly and that adoption of VR and AR solutions failed in some aspect. At this point, we have some indications of why that is the case; however, to form well-based conclusions, one would need to engage in additional data collection focused solely on finding the reasons for that situation.

Lastly, our project produced a set of recommendations on how to select training systems that match trainees' needs. We also created a set of recommendations aimed at increasing the probability of future training systems being adopted and used by a large number of prospective trainees.

Recommendations for Further Research

The large scale adoption of any solution is the ultimate goal in many domains; having tools that are widely and effectively adopted by a majority of intended users creates the necessary conditions for a paradigm shift in terms of dramatic change in the way those people operate. Having the majority of firefighters exposed to training solutions that effectively teach life-saving skills, and providing the surgeons with alternative ways of practicing their surgical skills in as near-realistic conditions as possible, are important goals that virtual reality (VR) and augmented reality (AR) communities aspire to.

Our recommendation for the follow-on effort is to focus on technology adoption across individual services; here, we have in mind the use of VR and AR solutions not only in the training domain but also in the operational environment. The goal of that investigation would be to identify a set of issues that affect the adoption of VR and AR systems; this also includes the issue related to the lack of their longevity over time, even when they are initially (successfully) adopted and used. This type of work would include extensive data collection across each service. As a form of data collection, we advise a mixed approach where a large number of individuals would be asked to respond to the online questionnaires, and a smaller number of individuals who are representative of typical groups of operators (novices, intermediate and experts) and instructors would be involved in focus groups and interviews. The type of data collected this way would help us further refine the model of technology adoption in DoD and identify specific issues that may be unique to a particular technology, in this case, VR and AR (Yates-2013; Sadagic-2015).

References

Yates, F. A. (2013). *Diffusion and Large-scale Adoption of Computer-supported Training Simulations in the Military Domain* (NPS Master Thesis) Sep 2013. Available from NPS Calhoun database.

Sadagic, A., and Yates, F. (2015). *Large Scale Adoption of Training Simulations: Are We There Yet?* Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC-2015), Orlando, FL

NPS-22-N081-B: Modeling High Power Microwave Engagements Versus Swarming Adversaries

Researcher(s): Abram Clark, and Isaac Kaminer

Student Participation: Maj Michael Wish USMC, and LT Nathan Redder USN

Project Summary

In this project, we theoretically and computationally studied several aspects of realistic high-power microwave-equipped (HPM) swarm-on-swarm engagements. Our prior work developed a framework for modeling and optimization of defense tactics against an attacking swarm. Here, we considered how this framework should change based on HPMs. We demonstrated how the parameters in our modeling and

optimization framework, specifically those characterizing the weapon effectiveness profile, can be obtained by direct antenna modeling of HPM weapons. These profiles can then be fed into our existing framework to provide optimal tactics to neutralize a threat. Additionally, we extended our previous work to include trade-off studies between different drone and weapons parameters (e.g., longer-range weapons but heavier and slower drones).

Keywords: *directed energy, high power microwave, swarms, drone swarm, automation, wargaming, engagement, modeling, adversarial autonomy, optimization*

Background

Previous work by Naval Postgraduate School (NPS) researchers has focused on modeling engagements between two enemy groups of autonomous agents (swarms) (Tsatsanifos et al., 2021). The core capabilities include physically realistic dynamic modeling, agent attrition based on a probabilistic field of effect for drone weapons systems, and an optimization framework to determine best tactics (Walton et al., 2022). HPM weapons represent an emerging technology for drone warfare, and HPM-equipped tube-launched drones are already being designed by DoD efforts. In particular, the Marine Corps is currently overseeing development of HPM-equipped drones via the MORFIUS program at Lockheed-Martin. There are several important outstanding questions about drones of this type, including the best tactics or performance limits of such systems as a function of the antenna design, the mobility of the HPM-equipped drones, or a slew of other design factors.

Our objectives for this project were to design a workflow where existing simulation capabilities could be combined with more realistic HPM-style weapons. With frequent communication between NPS and Naval Surface Warfare Center, Dahlgren Division, we demonstrated a workflow that could go from antenna design to a form that naturally could be input in our simulation framework.

Our second task was to demonstrate the feasibility of running such simulations. To this end, we used MATLAB's built-in antenna modeling toolbox to produce radiation fields for a half-wave antenna placed in a corner-reflector geometry, which is a garden-variety HPM antenna design. We then used the resulting radiation field, as well as intensity damage thresholds (which would need to be provided by external source such as experimental or field tests of lethality against certain drone types), to produce a weapon effectiveness field. This field was then run through our simulation framework.

Our third task was to design a quantitative framework for evaluating trade-offs in such simulations. This was primarily accomplished by LT Nathan Redder, who completed a master's thesis at NPS on this topic (Redder, 2022). LT Redder studied a simple case of a scattering red swarm that must be destroyed by a blue swarm. The blue swarm agents are equipped with weapons that have a specified range. Blue agents also have dynamical properties, namely a limiting speed and an acceleration time scale. LT Redder performed roughly one million simulations of such an engagement, where the numbers of agents were varied widely as well as the speed, acceleration, and weapons range of the blue agents.

Our methods were existing simulations, which are implemented in MATLAB, as well as MATLAB's built-in antenna-design toolbox. The workflow includes antenna design, which then leads to a radiation profile. The radiation profile can then be converted into a weapon attrition field, which can then be fed into our agent-based simulations. We also ran such simulations to demonstrate that the antenna profile had a direct effect on the outcome of the optimization.

Findings and Conclusions

Our first major accomplishment was demonstrating the feasibility of direct modeling of HPM weapons in our adversarial autonomy simulations. We successfully used the antenna-design toolbox in MATLAB to build an attrition rate profile for a model HPM weapon, which then was used in a simulation. We confirmed that changing the antenna radiation profile and re-running the optimization led to a different path taken by the defender. This demonstrates the feasibility of directly modeling HPM weapons in a modeling and optimization framework to choose the best HPM weapon parameters for a specific kind of engagement.

Additionally, we demonstrated how scaling analysis should be applied to determine the optimal parameters for drone and HPM design. In particular, LT Redder's thesis showed that an analysis technique called Buckingham's pi-theorem could be utilized to search for formulas relating a performance metric (time for the blue swarm to kill all red agents) to all input parameters to the simulation. The resulting formula allows mission planners to directly compare different inputs and answer questions related to trade-offs. For example, LT Redder studied how a global targeting algorithm (where blue drones are prevented from targeting the same enemy in the red swarm) and intercept-based flight planning (where blue drones plot a course to intercept enemy red drones rather than flying toward their current position). LT Redder also used scaling analysis to study trade-offs between drone flight characteristics and weapons range. His results showed how large numbers of simple simulations can be used to extract simple, often counterintuitive formulas that give a performance metric as a function of all system parameters. The models used were simple, but they demonstrated a powerful method that can be applied to more realistic scenarios.

Recommendations for Further Research

For future work, we recommend that researchers who have more familiarity with the design space of high-power microwave (HPM) weapons perform similar studies with increased specificity. Our approach demonstrates how to optimize performance for engagements of drone swarms equipped with mobile HPM weapons. Making HPM weapons easily mountable on airborne drones presents many technical challenges, so we recommend extension of our work for ground-based or ground vehicle-based HPM weapons.

References

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NPS-22-N187-A: Additive Manufacturing and Testing of High Metal Content High Performance Ramjet Grains

Researcher(s): Ibrahim Gunduz, and David Dausen

Student Participation: LT Nathan Couteret USN

Project Summary

Fuels with good combustion efficiency and high energy densities are needed to maximize the range and speed of future air-breathing systems. In order to achieve a higher energy density fuel, reactive metals are used as additives. In order to develop and maximize the energy density and performance, this work will leverage recent advancements in additive manufacturing (AM) to test low-density lattice structures using a new kind of 3D printing technology called liquid metal printing (LMP). LMP allows the rapid low-cost printing of aluminum alloys that can be used for producing parts for use in air-breathing systems.

This study investigated the 3D printing of aluminum lattices using LMP (Xerox ElemX) and successfully produced a number of parts with low-density infills with gradient patterns and dimensions. The study verified some of the dimensional constraints and capabilities of the commercial system, relevant in these applications such as the minimum feature size. Preliminary work with a modified nozzle system improved upon this limitation to print parts down to a feature size of 0.4 mm and produced some recommendations on further work with the system for air-breathing propulsion applications.

Keywords: *additive manufacturing, AM, 3D printing, liquid metal printing, LMP, aluminum alloy, propulsion, air-breathing*

Background

Fuels with good combustion efficiency and high-energy densities are needed to maximize the range and speed of future air-breathing systems. In order to achieve a higher energy density fuel, metals are used in these applications. Fly out calculations performed by Naval Air Warfare Center Weapons Division (NAWCWD) show that these systems could increase range by up to four times as compared to regular munitions. However, achieving this is challenging, which also presents a great opportunity. Increased range and speed can have significant impact on system effectiveness at the battlefield. NAWCWD (as well as others) have a great interest in these systems.

This work will leverage recent advancements in additive manufacturing (AM). This study investigated the 3D printing of aluminum lattices using liquid metal printing (LMP). LMP is a new technology developed by Xerox and the Naval Postgraduate School was one of their first partners that had the opportunity to work with their unique high technological readiness level prototype system called ElemX. The system produces and deposits aluminum alloy droplets in a controlled way to 3D print parts rapidly. As with all new systems, the capabilities and their potential limit on part design were unknown and these were the major research questions in this study.

The study verified some of the dimensional constraints and capabilities of the commercial system, some of which can limit its use in these applications such as the minimum feature size. This work investigated the printability of a number of relevant low-density lattice structures with varying densities and feature sizes using LMP. The part dimensions were measured for comparison to the design values to assess print quality. The system resolution was also improved down to a feature size of 0.4 mm, providing new opportunities to use this system for air-breathing propulsion applications.

Findings and Conclusions

For this study, a number of lattice designs were investigated. Initial designs included regular lattices with uniform voids for simplicity. These forms had 50% void space with rhombic channels and minimum feature sizes of 0.8 mm, which is the droplet splat diameter, and it represents a single droplet. This geometry was not suitable for LMP, resulting in collapse of the channels at bottom layers.

The designs were further refined into different kinds of gyroid lattice structures with improved printability. Gyroid patterns have lower overhang angles compared to other lattices and are isotropic. Lattices with gyroid patterns could be successfully printed down to the feature size of 0.8 mm with ElemX. Lattices with gradient porosity from top to bottom could also be produced, where the void fraction was the highest at the top. Multiple identical parts (up to five) printed at the same time showed a significant deviation on part height and mass, which was discovered to be a bug in the software used. This allowed correction of this issue after an update.

A modification to the nozzle to reduce the opening size from 0.5 mm to 0.25 mm allowed a reduction in the droplet diameter, doubling of the system resolution. A new higher resolution gyroid lattice with a minimum feature size of 0.4 mm could be 3D printed using the finer nozzle.

Our results show that relevant aluminum lattice structures with low density and density gradients can be rapidly printed with no supports down to a feature size of 0.4 mm, which is a very high value reported for directed energy deposition AM approach. This length scale provides some new opportunities for using these parts in air-breathing systems and should be further investigated for direct applications in follow up studies for rapid transition. NAWCWD has great interest to test the performance of these parts and provide relevant designs for implementation.

Recommendations for Further Research

Our results showed great promise for the metal 3D printing approach proposed and implemented in this study for air-breathing propulsion applications. Lattice structures with application tailored geometries should be investigated in future studies. Further reductions in feature dimensions down to 0.1-0.2 mm can be implemented based on the nozzle modification approach employed in this study, making it comparable to powder bed fusion additive manufacturing approaches. Finally, other aluminum alloy types should be investigated that can provide optimal properties and performance for a number of components.

References

None

NPS-22-N188-A: Impact of Autonomous Robot Assisted Proactive Grooming on Underwater Hull Cleanliness

Researcher(s): Jarema Didoszak, and Young Kwon

Student Participation: LT Sam Royster USN

Project Summary

Ships are continuously under attack by marine growth that stems from biodiverse micro and macro marine organisms attaching and spreading along the underwater hull surface. This is problematic due to the serious corrosion effects, unwanted vessel noise, reduction in flow through sea chests, and spreading of invasive species. Prior studies have shown that the accumulation of biofoulers can increase the hydrostatic volume and hydrodynamic friction of the ship thus increasing fuel consumption while robbing the ship of power and speed. Management of marine biofouling via underwater ships husbandry not only reduces the overall time a ship is in dry-dock but also mitigates these costly detractors while retaining the ship in an operational status. While the periodic removal of biological fouling via grooming has been shown to increase efficiencies, the true value in reducing adverse environmental impacts associated with reactive cleaning and out of water hull cleaning has not been well documented. It is theorized that the use of remotely operated vehicles and autonomous submersible devices employed in proactive hull grooming may provide even further benefits in schedule and cost savings over manual

grooming methods. The investigation of event periodicities, application to conventional hull surface preparations in typical surface ship hull areas were studied. Correlation of benefits with recommended proactive cleaning schemes, autonomous or remotely operated vehicle (ROV) utilization, and development of functional relationships point to expanded use of robot-assisted proactive grooming as another viable tool to keep marine growth on ship hulls at bay.

Keywords: *biofouling, fuel efficiency, remotely operated vehicle, ROV, unmanned undersea vehicle, UUV, hull fouling, hull grooming, ship husbandry, unmanned underwater vehicles, fouling pressure,* CO_2 *emissions, proactive grooming, autonomous systems*

Background

While it is well understood that the accumulation of biofouling on ship hulls and appendages is detrimental to the cost-effective operation of ships at sea, it is less evident where the introduction of automated systems being utilized for proactive grooming would make the greatest impact in minimizing the occurrence of unacceptable fouling pressures.

The management of hull cleanliness is based on several factors. Variations in ship schedule, ship service speed, port environmental conditions, cleaning technique, and periodicity, all complicate the typical cost-benefit equation. Each element contributes as a weighted function against the cost, schedule, and performance of the ship system. When discussing applications for the U.S. Navy, an additional layer of complexity is introduced as naval vessels rarely follow set schedules, visit the same ports throughout the year, nor follow strict hull cleaning schedules due to ever-evolving mission requirements. Unlike commercial vessels which are optimized around profit, naval vessels are predicated on operational capability. While an increase of half of a knot in ship service speed would undoubtedly be welcomed by ships' captains, the true benefit is potentially lost on a navy's ability to show actual value from this gain as a result of uncontrollable events. Likewise, the capability to accurately track incremental gains from underwater hull cleaning is difficult at best due to fluctuating sea conditions, changes in wetted surface area, and unrelated maintenance schedule driven propulsion plant performance.

The focus of this study was to investigate how the implementation of autonomous robot-assisted systems in the proactive grooming process would impact the overall efforts of combating marine growth. Through the analysis of research findings in the emerging area of proactive grooming of ship hulls, traditional reactive cleaning case studies and other investigations, correlations were able to be made in estimating the necessary resources against predicted benefits. Specific performance considerations sought out included the overall reduction in fouling pressures with respect to ungroomed surfaces, the effect of grooming frequency on traditional surface coatings, the characterization of damage to surface coatings with repetitive grooming operations and dependence on temperature driven growth rate impacts on cleaning periodicals based on vessel schedule and pierside duration.

Findings and Conclusions

The drydocking and associated deep cleaning and preservation processes as part of the ship's overall maintenance scheme is the gold standard which all other hull cleanings are gauged. While reactive in-water hull cleanings on average provide a 20-25% reduction in added resistance, this advantage decreases linearly as a function of time. Recent studies indicate a comparable level of hull fouling reduction can be realized through proactive means, namely periodic grooming. However, both processes which provide significant gains are concentrated on cleanliness of the typical hull area of a vessel, which primarily includes the midbody other areas of mild structural curvature. Running gear, hull appendages, penetrations, and high gradient areas of the submerged structure such as bulbous bows are excluded for these results, whether approached via manual cleaning or robotics assisted cleaning operations.

With regard to performance, while the reactive cleaning process is extremely effective in removal of hull fouling through the nature of the physical abrasion, it too damages the hull coating and potentially exposes underlying metal of the ship hull to a) stand unprotected until the next drydocking period, b) accumulate higher fouling pressures more quickly due to an absence of resistive coatings and c) introduces greater amounts of toxic effluent into the underwater environment due to the removal process. Even with the higher periodicity of contact over reactive type cleaning methods, it has been concluded that proactive grooming using a less abrasive method has the potential to maintain acceptable fouling pressures. This can extend the periodicity of labor intensive out-of-water (drydock) hull cleaning without the resulting surface damage to hull surfaces. Additionally, it can help limit the introduction of toxicity into the environment via the cleaning operation.

The introduction of automated, autonomous or robot assisted cleaning is not a new concept. Research indicates that for the general areas of the ship hull, there is no reason not to adapt this practice in either reactive or proactive cleaning. This study did not specifically address the unique areas such as hull appendages where considerable effort is spent in time and resources due to the unique geometries and accessibility issues.

In dealing with hull fouling accumulation and the ability to provide cost savings analysis of proactive grooming using automated systems, the current work was inconclusive. Tracking of a ship's data to the degree necessary for this investigation was not made available due to the difficulty of parsing inconsistent data and potential security implications. It is proposed for future work that a representative U. S. Navy vessel, such as an Arleigh Burke-Class destroyer, be fully instrumented with specific sensor equipment to record high fidelity and frequency measurements of water temperature, geographic location, sea state (including current estimation), ordered speed, speed made good, windspeed, draft, and other engineering data to correlate with the actual hull cleaning state. In lieu of this, detailed open ocean field testing of surrogate models reactively and proactively cleaned over a substantial period and subjected to sporadic movement and representative flow velocities could be used to inform the outcomes more definitively than qualitative study of sparse historical ship data.

Recommendations for Further Research

The introduction of autonomous hull cleaning robots and their accompanying subscription cleaning services has launched a new offshoot to the traditional reactive hull cleaning model. Largely focused on flat or gradually curving areas of the underwater hull area, fundamental issues such as grappling with navigation algorithms and positioning glitches have given way to challenging speed limitations and cleaning swath constraints. While many of the past physical issues have been minimized, matching periodicity to proactive grooming for vessels with dynamic schedules and fluctuating voyage plans still needs to be refined. Studies in the use of automated undersea robotic systems used for proactive grooming have centered largely on surrogate stationary panels being serviced at various routine schedules rather than on vessels circumnavigating the globe in apparently ad hoc cycles as driven by DoD missions rather than dictated by route planning such as in the case of commercial shipping, where exact schedules drive costs. A better understanding of the true operational impacts and cost benefits associated with these preventative actions needs to be extrapolated onto the sum of the fleet. Additionally, the current use of autonomous robot-assisted cleaning devices is relegated to approximately 80% of the underwater hull surfaces which are mostly flat and easiest to access. Tradeoffs involving the losses endured through avoidance of niche areas such as sea chest openings, running gear, and other appendages as compared to the cost of using dedicated manpower in diver-facilitated reactive cleaning is yet to be fully determined.

References

None

NPS-22-N200-A: MQ-25A Manned/Unmanned Teaming

Researcher(s): Scot Miller, and Dan Boger

Student Participation: Capt Andrew Benton USMC

Project Summary

The MQ-25 is an unmanned aircraft system (UAS) designed to operate from an aircraft carrier and perform air-to-air refueling (AAR) and intelligence, surveillance, and reconnaissance (ISR) for the carrier air wing (CVW). This will relieve manned platforms, such as the F/A-18, from conducting these missions, thereby preserving manned flight hours and extending F/A-18 service life. Current UAS operations rely predominantly on human teams connected through beyond line-of-sight communications (BLOS) links. This architecture is insufficient to ensure MQ-25 mission accomplishment in an operational environment characterized by uncertainty in the electronic magnetic spectrum (EMS). Manned aircraft have pilots in the cockpit making tactical, context driven decisions and must be complemented by competent unmanned teammates; the MQ-25 has the potential to be this teammate. To this end, we employed interdependence analysis (IA) and co-active design to examine the human-machine interface and identify areas for increasing instances and proficiency of human-machine teaming (HMT), especially through the consideration of observability, predictability, and directability.

From this analysis, recommendations in system design, employment, and other functional areas were made that enhance mission accomplishment and system performance and resilience in uncertain EMS environments. These include the creation of a common Joint Planning and After-Action System (JPAAS) digital mission planning system to enable semantic interoperability between manned and unmanned systems and a sense and detect capability on the UAS to generate better unmanned situational awareness and promote possible cognitive decision making, especially in contested EMS operations. Warfare is inherently a team enterprise, and the efforts to fully automate it are misplaced. The value to be gained in HMT comes from utilizing the strengths of each team member to maximize effectiveness.

Keywords: *MQ-25, human-machine teaming, HMT, interdependence analysis, IA, digital planning, unmanned aircraft systems, UAS, intelligence, surveillance, reconnaissance, ISR, beyond line-of-sight, BLOS, observability, predictability, directability, OPD, mission planning, Joint Planning and After-Action System, JPAAS, electromagnetic spectrum, EMS*

Background

In the early 2000s, the Navy sought an aircraft that would serve as an unmanned combat aircraft vehicle (UCAV). At a 2008 Naval Postgraduate School concepts wargame, UCAV participants raved about how it would serve as the predominant naval strike aircraft of the future. Other participants suggested that with its lengthy flight endurance, it could also serve as an ISR platform. While UCAV aircraft carrier operations development proceeded with successes, mission design faltered. In 2016, the Navy decided on making UCAV a primary mission and overhead tanker, with ISR capability as a secondary mission. Called the MQ-25, it extends the strike range of existing F/A-18 aircraft and relieves them of their tanker role.

While manned aircraft coordinate with voice, hand signals, and lights, coordination with the MQ-25 is accomplished through an air vehicle operator (AVO), connected through beyond line-of-sight communications. Degradation of that communications link inhibits operational capability.

Designing for human-machine teaming may reduce that degradation in MQ-25 missions. Further, advanced human-machine teaming capability will enable force multiplier mission support, increasing the carrier air wing's warfighting capabilities.

Co-active design and interdependence analysis (Johnson, 2014) are two proven methods for identifying human-machine teaming requirements and generate resilience, reliability, and potential pitfall considerations. Proper identification of these requirements enables focused research and development of human-machine paired systems that truly enhance mission effectiveness. With the desire to introduce additional capability to the MQ-25 platform and the increasing likelihood of contested EMS environments, the MQ-25 must perform its current and future missions of tanking and enhanced ISR in these environments.

During the co-active design phase, researchers developed an operational view to display the mission scenario and hybrid operational concepts between the MQ-25, receiver aircraft, and the AVO. Researchers first performed systems functional analysis to identify specific process steps then used the co-active design approach to develop HMT requirements in terms of observability, predictability, and directability to display the interdependency relationships between the three systems.

As mentioned, BLOS communication links are subject to being denied or degraded, making assured mission success problematic. Using the co-active design process enables recognizing what computational and decision capability must be pushed as close as possible to the tactical edge to minimize environmental effects on mission accomplishment. Strike and other manned aircraft have humans in the cockpit making tactical decisions and, therefore, ought to be complimented by competent, capable, and predictable unmanned teammates to maximize mission effectiveness from both manned and unmanned platforms.

The analysis leveraged sponsor-defined use cases, to include enhanced ISR and other aviation operations, in contested network and communications environments. These requirements are intended to be incorporated into the MQ-25 and subsequent type, model, series of the system, and are meant to focus and enhance subsequent efforts to allow the MQ-25 system to partner with human operators in the conduct of tanking, ISR, and other missions in support of fleet operations.

Findings and Conclusions

UASs have long been conceptualized as human capability extenders, increasing reach and staying power. While this valuable capability has served the force well, the time has come to move beyond. UAS operations need not be on either extreme end of a spectrum that spans from human-in-the-loop operations to purely autonomous systems operating in a fire and forget manner. Warfare is inherently a team enterprise, and the efforts to fully automate it are misplaced. The value to be gained in HMT comes from utilizing the strengths of each team member to maximize effectiveness.

The United States Navy needs a digital mission planning system (in this research, it is called the Joint Planning and After-Action System, or JPAAS) with one ontology for all missions, that all air wing and other impacted mission platforms employ. JPAAS would enable semantic interoperability of all CVW systems, manned and unmanned, a critical component of any non-permissive teaming effort. This eases information exchange, since the data framework and structure would be common across platforms, increasing teaming among aircraft and surface ships. After mission completion, JPAAS would be included in the after-action review process so that the entire planning team can evaluate the effectiveness of their planning decisions.

Utilizing the AVO as an information conduit or as the primary source for cognition does not utilize the MQ-25 as an unmanned teammate but rather as a capability extension. The inclusion of a sense and detect (S&D) system to the MQ-25 will create opportunity for true human-machine teaming in permissive environments and enable successful mission completion by the unmanned teammate in non-permissive environments. The S&D system is envisioned to provide perceptive and cognitive capabilities to the MQ-25, where only limited performative characteristics currently exist. The ability for the MQ-25 to perceive its environment and make recommendations or decisions, depending upon the environment, is crucial to its ability to operate in the future environment.

For instance, in AAR, safety dictates only critical, relevant information be transmitted to enable refueling. The MQ-25's ability to prioritize and select the appropriate information is vital. Starting with doctrinal parameters, this S&D system would use machine learning (ML) to increase decision capability in permissive operations when teaming with human operators, building trust for when human teammates are unavailable. JPAAS integration allows planning iterations, including unexecuted missions, to contribute to the training of the S&D ML algorithm. The introduction of a system that interacts with the human teammate beyond displaying system status information is key to moving beyond human-human teaming with an unmanned intermediary.

Humans have the capacity to work with many different teammates. The MQ-25 should be given the ability to do the same. Allowing the MQ-25 to communicate directly with teammates, particularly in AAR, expands human-machine teaming opportunities, decreases associated delays, and builds system resilience during periods of AVO-UAS non-connectivity. This improves CVW resilience and increases system flexibility by opening alternative communications pathways.

Recommendations for Further Research

Four broad areas emerged that require further research. The Joint Planning and After-Action System (JPAAS) system would enable semantic interoperability at the system level for aircraft and systems fleetwide. Such a system also expands human-machine teaming potential to planning and after-action phases of operations, creating opportunities for increased trust and training the respective machine learning (ML) algorithms. A JPAAS system should be explored in greater detail to enable the key capabilities, particularly in the areas of underlying message structure, ML algorithms, and how the system would interface with its human teammates and other unmanned systems fleet-wide. The goals set forth in the Navy's Project Overmatch present a unique opportunity to bring a system, like the one posited here, to fruition.

A theme that emerged throughout this research was the reliance on the air vehicle operator (AVO) for many critical functions during execution. A non-permissive environment removes the AVO from the situation, meaning the MQ-25 must be capable of teaming with the receivers or any other aircraft relevant to its mission, necessitating communication between those entities. Examination of a direct communications link from MQ-25 to receiving aircraft would enable this teaming possibility, increasing the likelihood of safe mission accomplishment. A detailed interdependence analysis (IA) of this human-machine team could provide valuable insights as to precisely what cognitive capabilities should be included in the MQ-25. Additionally, examination of the technical aspects of this communications link, such as J-series message standardization, or other short-range communications methods should be examined to enable data communication. Air-to-air refueling (AAR) operations currently involve extensive use of voice communications, and technologies such as natural language processing should be explored to enable the MQ-25 to communicate in this manner as well.

Another theme that emerged in this research was the complexity of aviation command and control (C2) and the many entities involved. IA, or other analytical methods, should be applied to the C2 structure that surrounds the MQ-25 to include the many entities with which the AVO currently coordinates to understand how to better integrate the MQ-25 into this structure and improve communications efficiency. Additionally, this analysis would reveal insights as to how this structure may need to adapt to better support the types of operations desired in the future that may be data centric but where periods of non-permissibility are commonplace.

The recommended sense and detect system requires the inclusion of additional sensors and data processing capacity onboard the MQ-25. Among those discussed were environmental and navigation sensors, natural language processing, transmission media evaluation, and ISR data prioritization. Non-permissive electro-magnetic spectrum (EMS) environments will require pushing computational capability to the tactical edge, rather than retaining it at centralized stations connected by long-haul communications links. Mission accomplishment in these uncertain EMS environments will not be possible without increasing the processing capacity resident on the MQ-25 platform to perform these processes and requires additional study.

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NPS-22-N219-A: Common Message Sets Across Data Links

Researcher(s): Brian Wood

Student Participation: No students participated in this research project.

Project Summary

The United States military operates data links across multiple mediums to pass battlespace information.

Existing links (e.g., Link 16, CEC, and Internet Protocol [IP] based links) are capable of sharing track data, often manually by an operator. Once the track data is moved off its original link it will lose most of its properties. Thus, such a track will be stripped of the required fidelity for employment. In addition, the stove-piping of kill chains into one data link increases its vulnerability, as the threat must only disable one node or deny one medium to render it inert. After consulting subject matter experts on data link background material and obtaining feedback, a proposed methodology was identified to address the transfer of data issue.

Three systems that address data link transfer, Marine Air Ground Task Force Agile Network Gateway Link (MANGL), Rich Semantic Track (RST) Ontology, and System-of-systems Technology Integration Tool Chain for Heterogeneous Electronic Systems (STITCHES), were examined with investigations into their background and usage were conducted. Using a multi-criteria decision analysis (MCDA) the effectiveness of the three options were analyzed and an ordered list of alternatives were given. MANGL performed well (top score) in every criterion with MANGL a close second—behind due to it not being a program of record. Both have shown they are technically proficient and should be further examined for passing common message sets across disparate links. RST also offered possibilities; however, additional research is needed in developing an actual prototype before moving forward with it as an established program. MANGL, a Marine Corps program should be closely examined by the Navy and STITCHES should continue to be incorporated into Navy exercises and demonstrations.

Keywords: *data link, multi-criteria decision analysis, MANGL, rich semantic track, STITCHES*

Background

MANGL is a network gateway and software payload that is not unlike an intelligent airborne retransmit site. But, unlike others, this site taps into multiple different networks and funnels prioritized information into a common tablet interface that is wirelessly updated from radios that users already carry. MANGL is the bridge that enables true digital interoperability, providing SA that has been previously unavailable due to stove-piped networks (USMC, 2020).

RST Ontology argues for putting data into a common framework where other formats could be created and enabling a large set of tools to function in the common data format. In his doctoral dissertation, Curt Blais stated that he “kept the core conceptual model VERY simple, but [RST Ontology] could be enhanced with any information that people feel would be needed to create an even richer information exchange environment” (Blais, 2022).

STITCHES is a software toolchain designed to rapidly integrate assorted systems across any domain by creating extremely low latency/high throughput middleware among these systems without software changes or upgrades to hardware (DARPA, 2020).

Subject matter experts were consulted on background material and provided feedback on appropriateness of proposed approaches and methodologies.

MCDA is a structured process for evaluating options with conflicting, multiple criteria and choosing the best solution. An MCDA solution allows the decision maker to determine the effectiveness of available options, thereby increasing efficiency. In addition, it uses a systematic approach, presents an ordered list of alternatives, helps further communication among stakeholders, and provides useful insights.

A six step MCDA process was used for this research, as follows:

1. Define the objective: Find a method to modify current data links to allow track data to be passed across different data links while maintaining the data's original properties.

2. Define the criteria to be analyzed:
    a. Maturity – what is the level of development of the system?
    b. Current Use – how is the system being used today?
    c. Modify Links – can the system modify current data links?
    d. Pass Data – does the system allow track info to be passed?
    e. Track Properties – does the system maintain the original properties of the track?

3. Each criterion was assigned a grade of 1-5, with 5 indicating the criterion was fully realized and minimal work needed to be done to reinforce current plans or documentation for this system, while 1 indicated there was little to no documentation or discussion of the system in the criterion and large amounts of work needed to be done (Schuck, 2022).

4. The weight of each criterion was assigned based on its relative importance in completing the objective. Maturity and Current Use were assigned 50% and the remainder 100%.

5. The three choices: MANGL, RST, STITCHES were listed.

6. Performance values (grades) were assigned to each criterion for each system choice and compared both by the raw (grade) score and the weighted score (grade x weight %). Each set of scores were summed to give an overall weighted performance score for each option.

Findings and Conclusions

The final weighted performance scores are MANGL (20), STITCHES (18.5) and RST (10.5).

Based on MANGL having a grade of 5 for every criterion, it was expected that it would finish as the top performer. However, STITCHES is a relatively close second place, taken out only due to its not being a program of record and not having as much active involvement in military events in the past two years (lower grades for Maturity and Current Use). However, it has been able to fully demonstrate in the three remaining criteria (Modify Links, Pass Data, and Track Properties). RST has an outstanding theoretical basis for being able to execute the objectives of the common message set effort, but it has not had any traction in the four years since it was published in Blais's 2018 dissertation.

Both MANGL and STITCHES should be further examined for working on passing common message sets across disparate links. They have shown that they have the technical ability to conduct these missions. While RST also offers possibilities, additional research is needed in developing an actual prototype before moving forward with it as a program of record.

Recommendations for Further Research

The architecture of the Marine Air Ground Task Force Agile Network Gateway Link (MANGL) could be used to demonstrate possible data transfer scenarios in the Navy.

It would be beneficial to have System-of-systems Technology Integration Tool Chain for Heterogeneous Electronic Systems (STITCHES) participate in Navy experiments from the operational to small technical levels, such as Valiant Shield, Trident Warrior, Joint Interagency Field Experimentation (JIFX).

Additional master's thesis work working on Rich Semantic Track (RST) would be helpful in the common message set arena.

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NPS-22-N263-B: Ultrahigh Temperature Materials for Hypersonic Systems Readiness

Researcher(s): Claudia Luhrs, and Troy Ansell

Student Participation: Alec Saldana, and Ronan Patel

Project Summary

To achieve the strategic and operational goals required for the survivability of aircraft traveling at hypersonic speeds, it is imperative to study which materials could serve as thermal protection, capable of withstanding extreme heat and oxidative and ablative conditions. The study conducted aimed to support the hypersonic RDT&E efforts by validating the use of diverse fabrication routes as an operational alternative to generate the ultrahigh temperature ceramics (UHTC) zirconium diboride (ZrB_2) and silicon carbide (SiC). The work included the integration of the UHTC as the surface layer of composites containing graphitic fibers and carbonaceous matrices. A technical assessment was performed to determine if the newly achieved composite materials had the chemical makeup and microstructural characteristics desired employing scanning electron microscopy and X-ray diffraction techniques. The study evaluated the potential of the composite to withstand oxidative and ablative conditions encountered by systems used in hypersonic flight, simulated by the use of an oxygen acetylene torch.

The carbothermal reduction of zirconium oxide employing boron and carbon black as precursors, at temperatures in excess of 1450°C, rendered high-purity ZrB_2. The use of a one-component liquid precursor (SMP-10) successfully produced diverse polymorphs of silicon carbide (SiC). ZrB_2 and its mixture with graphite did not present significant morphological changes after exposure to ultrahigh temperatures; however, ZrO_2 peaks of reduced intensity were detected in their XRD patterns, with those containing graphite being smaller than the bare ZrB_2. SiC from SMP-10 produced a glassy sintered byproduct, while commercial SiC did not suffer any changes. Zirconium diboride exhibited the potential to withstand extreme environments, as initially hypothesized. Future efforts should include the evaluation of mechanical properties of the sintered composites.

Keywords: *ultrahigh temperature ceramics, UHTC, hypersonic, transition metal borides*

Background

When hypersonic speeds (3000 mph and above) are reached, the friction between air and the high-speed object generates extremely high temperature regions (>2000°C), high mechanical stresses and a decrease in the materials' tolerance to damage. Those severe conditions call for the use of new, highly engineered materials that can withstand not only high temperatures, but also environments that tend to oxidize the components of the system passing through at those speeds, which reduces their strength and causes erosion and material degradation. Ceramic tiles have traditionally been used for aircraft thermal protection; however, their brittleness, low damage resistance and high cost have limited their application. Metallic thermal protection structures, super alloys, and intermetallic compounds have also been considered; however, their melting temperatures and susceptibility to oxidation are drawbacks. Therefore, the search for ultrahigh temperature resistant materials is still a fertile area of research. Recent advances in the field suggest that ceramic materials, such as transition metal borides integrated with carbonaceous matrices and silicon carbides, have the potential to withstand ultrahigh temperatures and conditions such as those encountered during hypersonic flight.

Findings and Conclusions

The carbothermal reduction of zirconium oxide employing boron and carbon black as precursors, at temperatures in excess of 1450°C, rendered a higher-purity ZrB_2 than the specimens generated by atmospheric plasma fabrication approaches, and based on the data collected by this study, is the most indicated method to produce zirconium boride. The use of a one-component liquid precursor (SMP-10) successfully produced diverse polymorphs of silicon carbide (SiC). The precursor decomposition takes place in three stages and can be readily mixed with ZrB_2 without promoting its oxidation once the SMP-10 samples have suffered the initial decomposition step at 160°C.

ZrB_2 and its mixture with graphite did not present significant morphological changes after exposure to ultrahigh temperatures; however, ZrO_2 peaks of reduced intensity were detected in their XRD patterns, with those containing graphite being smaller than the bare ZrB_2. Zirconium diboride, thus, has the potential to withstand extreme environments, as initially hypothesized.

SiC from SMP-10 produced a glassy sintered byproduct, while commercial SiC did not suffer any changes. Carbon nanotube composite mixtures presented the largest levels of oxidation due to the presence of the iron employed as catalyst during their production, which turned into FeO and Fe_2O_3, depending on the nanotube location in the mixture, internal or superficial, respectively.

Recommendations for Further Research

Since there are no standard methods to test ultrahigh temperature ceramics, if the use of an oxygen acetylene torch is to be continued, an in-situ temperature monitoring system or probe should be employed to accurately determine treatment conditions and their effects. High power lasers should be also considered.

Further research should include mechanical properties assessment of sintered monoliths of the diverse zirconium boride, silicon carbide, and carbonaceous combinations.

References

None

NPS-22-N306-A: Distributed Closed Loop Fusion for Distributed Maritime Operations (DMO)

Researcher(s): Jihane Mimih, and James Scrofani

Student Participation: No students participated in this research project.

Project Summary

The DOD seeks to conduct all-domain operations and requires intelligence, surveillance, reconnaissance, and targeting (ISRT) across all domains of conflict. For the Navy, this includes the deep seabed, undersea, sea surface, air, space, and cyberspace operations. All domain ISRT encompasses and integrates information from sensors across all domains of the maritime environment—sensors and sources from "Seabed-to-Space"—to provide commanders with the most complete picture of adversary activities. This capability supports the Navy approach to Distributed Maritime Operations (DMO), an operational concept that enables widely dispersed naval units to perform sensing, command and control, and weapon activities such that the distributed platforms act as a coherent whole. All-domain ISRT requires a network to enable widely dispersed sensors to exchange, correlate, and combine sensor data (the fusion of data) to provide a complete understanding of the operational picture and to provide targeting information for long-range engagement required by DMO.

This study modeled and evaluated the role of persistent low earth orbit (P-LEO) space constellations and autonomous vehicles and vessels for sensing and network relay to enable over-the-horizon ISRT. Our findings show that the coordination of sensors via P-LEO space constellation relay is feasible, though complex, and enables DMO over-the-horizon operations for surface warfare long-range cooperative engagement. We analyze and model the orchestration of the diverse P-LEO sensors and the coordinated use of autonomous vehicles to enable coordinated fires. Our study has demonstrated how a constellation of imaging sensors and relay satellites will enable distributed search, detection, and tracking with local unmanned air and surface vehicles' support for terminal engagement.

Keywords: *distributed maritime operations, DMO, tasking, collection, processing, exploitation, dissemination, TCPED, seabed-to-space, AI, artificial intelligence, C5ISRT, command, control, communications, computers, cyber, intelligence, surveillance, reconnaissance, targeting, DoD, Department of Defense, ISR, intelligence, surveillance, reconnaissance, targeting, ISRT, autonomous vehicles, autonomous vessels, JADC2, joint all-domain command and control, P-LEO, persistent low-earth orbit, ML, machine learning*

Background

The study of networked sensing and distributed collection of ISR information has been addressed at a theoretical level for over 25 years to measure the performance gains from distributed detection, correlation of features from distributed sensors and sources (MultiINT), and inferential reasoning from diverse networked sources. This theoretical foundation provides a basis for understanding the performance (detection rate, recognition accuracy, timeliness, etc.) and effectiveness (targeting accuracy, update rates, etc.) of distributed sensing, but does not address the achievable capability for such extreme cases of the all-domain problem.

This research defines the practical MultiINT collection options against maritime targets and studied the complexity of tasking, collection, processing, exploitation, and dissemination (TCPED) activities required to orchestrate space and surface activities against dynamic and fleeting maritime targets. We conducted this research in cooperation with the Naval Information Warfare Center Pacific (NIWC-PAC), who leads the development of ISR and information operations systems that operate with manned and unmanned platforms, including tactical data communications platforms, satellite terminals, autonomous systems or nonautonomous platforms. This research will support the NIWC efforts for DMO.

The research directly supports the focus of the Chief of Naval Operations (CNO) Navigation Plan issued January 2021 which focuses on the following elements:

As the plan states, "Emerging technologies have expanded the modern fight at sea into all domains and made contested spaces more lethal," which is enabled by the resilient command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting (C5ISRT) capabilities, all-domain coordinated efforts, and project synchronized lethal and non-lethal effects across all domains.

It continues by noting, "Ubiquitous and persistent sensors, advanced battle networks, and weapons of increasing range and speed have driven us to a more dispersed type of fight," because of the persistent sensors and information Naval Operational Architecture (NOA) that integrates with Joint All-Domain Command and Control (JADC2), resilient web of persistent sensors, command and control nodes, platforms, and weapons.

Also, according to the plan, "Advances in artificial intelligence and machine learning (AI/ML) have increased the importance of achieving decision superiority in combat", enabled by the ability to close the kill chain faster than our rivals, project synchronized lethal and non-lethal effects across all domains. (CNO, 2021, p. 4-5)

This research developed DMO scenario concepts and implemented computer models of one stressful surface warfare scenario to evaluate the feasibility of utilizing P-LEO) satellite constellations for sensing and network relay.

Findings and Conclusions

We demonstrate in our study the feasibility of such an approach. The results have shown, at the depth of analysis performed:

- Optimum configuration of a network of sensors and autonomous sensor platforms. We defined a combination of the DoD/ Space Development Agency (SDA) Tranche 1 P-LEO relay network, and suitable P-LEO EO/synthetic aperture radar (SAR) imaging spacecraft with a 30–45-minute revisit rate (represented in this study by commercial collection constellations in the 2025-time frame).

- Fusion methods to coordinate TCPED collection. Because of the relay capabilities, we found that, though sensing is distributed, a centralized data fusion approach was suitable for the configuration we modeled.

- Network Availability and latency. These are critical parameters that determine if the sequentially dependent process sustains custody of a target. Sustained outages (due to weather or jamming) have the potential to cause cascading errors (i.e., loss of availability leads to increased latency, and failure to sustain correct satellite observations- resulting in a loss of target custody). Latency limits in the process are required to assure the sensor data can be properly combined and sensors can be properly tasked to maintain the target track. We place this caveat in our feasibility statement: Availability and latency limits must be maintained.

- Fusion architecture to enable DMO Cooperative Engagement. A centralized fusion approach is satisfactory to perform the typical DMO surface warfare scenario with SDA Tranche 1 relay constellation and suitable 30-to-40-minute revisit imaging satellite constellations in the 2025-2030 timeframe.

- Orchestration of the diverse sensors from seabed tip-off to space sensing and UAS-UAV support to perform coordinated fires is complex but feasible when space relay constellations demonstrate high availability.

- A constellation like the planned DoD SDA constellation as modelled, or larger, will provide coverage to enable distributed search, detect, and track but will likely require local UAV and USV support for terminal engagement.

Recommendations for Further Research

This study has used modeling tools to statistically evaluate high risk areas that determine the feasibility of performing TCPED in such a distributed network - latency, availability, dynamic tracking. Future studies with greater fidelity could include, for example:

- Utilize the Naval Surface Warfare Center Mast Simulation tool (or similar) to create stressful Distributed Maritime Operations (DMO) scenarios that include multiple dynamic maritime targets with radio frequency, electro-optical and radar signatures.

- Use the Mast scenarios to drive a sensor and network model with transmission control protocol/internet protocol level fidelity to simulate the detection of maritime targets, relay of detection data, and control of sensors on the net.

- Include a fusion model to simulate the fusion and battle management functions to enable long-range engagement.

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NPS-22-N345-A: CNO Ship Availability Maintenance Team Workload and Manning

Researcher(s): Paul Beery, and Ronald Giachetti

Student Participation: Amy Lee, Marcus Chavez, Morgan Garone, Travis Kennamore, and Sydney Walton

Project Summary

The research project studied the planning process for major surface ship maintenance activities, termed availabilities, and sought to determine whether the Navy's estimates for maintenance availabilities could be improved. We analyzed data on the estimated and actual durations of surface ship availabilities conducted at the Southwest Regional Maintenance Center (SWRMC). For estimates, we narrowed the project scope to examine estimates for tanks and voids work conducted as part of each availability. Data was collected for 30 surface ships and various regression analyses were conducted, but none of the analyses showed any statistically significant relationships. We separately compared the contractor estimates of man-day requirements for complete availabilities to Navy estimates and found the contractors consistently underestimated the number of man-days required to complete the availabilities.

We also found a contributor to poor estimates is growth work, specifically requests for contract change submitted by contractors after the scope of work to be conducted as part of an availability is finalized. We found a correlation between growth work and maintenance delays. Likewise, we found a positive correlation between growth work and the age of the ship. One challenge was the lack of data on ship maintenance in a single database and the inconsistency in the maintenance data. The findings can help inform decisions on manning, resource allocation, and processes for surface ship maintenance planning and execution.

Keywords: *ship maintenance, availabilities, regional maintenance centers, project estimation, late projects, surface ship maintenance*

Background

As the US Navy faces an aging fleet, the ability to quickly perform maintenance activities is important for ship availability. The current CNO, Admiral Michael Gilday, set a goal of zero lost operational days due to maintenance by the end of FY21. This will require a substantial improvement on performance from 2020, when only 40% of ships had their maintenance completed on time. Ship maintenance has received substantial attention because the majority of scheduled maintenance availabilities are delayed, sometimes by years. These long delays impact operational availability of the ship.

The objective of the research was to conduct duration analyses that inform the development of future availability duration estimates. In particular, this project focuses on the Availability Duration Scorecards (ADS), which are used by both the Naval Sea Systems Command and Regional Maintenance Centers (RMCs) to allocate resources and personnel to individual availabilities. An availability describes when a Navy ship is made “available” for a major maintenance activity conducted in dry dock. The ADS is an important planning document for ship maintenance, and lateness is measured with respect to the duration estimate from the ADS.

There have been a number of related studies conducted in recent years to inform ship maintenance planning and execution. Caprio and Leszczynski (2012) investigated CNO availability schedule overruns and found aircraft carrier availabilities tend to finish on schedule more frequently than other ship classes; late availabilities charge less for work per month than the budgeted amount of work; and late availabilities generally have more work stoppages prior to the initiation of work than on schedule availabilities. Other studies were conducted by De Vlaming (2018) and Sears (2021), as well as the many reports generated by the Government Accountability Office (Mauer, 2022).

This research addressed the problem through the lens of lean systems thinking to identify bottlenecks and improve workflow. We evaluated the end-to-end process of maintenance from availability planning to execution. The project gathered data on ship maintenance from about 30 CNO Availabilities conducted at SWRMC from FY16 to FY21 for guided-missile cruisers (CGs), guided-missile destroyers (DDGs), and littoral combat ship (LCSs). The data was taken from multiple sources, including the Navy Data

Environment, Navy Maintenance Database, Ship Maintenance Data Improvement Initiative, and Ship Maintenance Model. The data was then combined into an MS Excel spreadsheet for analysis. We performed multiple types of regression analysis on the data seeking out any correlations between the independent variables (e.g., ship age, ship type, number of tanks and voids) with the dependent variables (e.g., availability duration, number of man days, and number of requests for contract changes).

Findings and Conclusions

We were able to find several interesting correlations in the ship maintenance data. One finding was the contractor estimations of the man-days required to execute an availability were consistently lower than the actual number of man-days required to complete the availability. Other estimates from the Navy Maintenance Database, Ship Maintenance Data Improvement Initiative, and Ship Maintenance Model provided more accurate estimates of the man-days required to complete availabilities. A second interesting finding was an increase in the number of requests for contract changes, i.e., growth work, for older ships and those ships that had extended deployments between availabilities. This finding was more noticeable for DDG class ships than for either CG or LCS class ships, likely due to the larger sample size available for DDGs. Other than these findings, the regression analyses were unable to find any statistically significant relationships in the data.

The inability to find statistically significant effects can be due to one or more of the following reasons. There may be no relationships between the variables, or we examined the wrong independent variables. The sample size was small and may have been too small for trends to emerge in the data. Notably there were several statistical trends that conflicted between ship class, such as the relationship between ship age and the number of requests for contract change. Due to the small sample sizes, we note the discrepancies rather than suggest an actionable conclusion to avoid building recommendations based on potentially spurious statistical relationships. The data was collected from multiple sources and may have had errors in it. Lastly, the unique aspects of each ship and the associated maintenance work on each ship results in a substantial number of exceptions being made to standard practices. While understandable, the uniqueness of the maintenance strategy for each ship is particularly challenging for large scale data analysis. These unique aspects and special circumstances create outliers in the data that skew the results.

The research work contributes to a greater understanding of the maintenance process. The SWRMC can take the results and investigate how contractors make their estimates, and they can also explore the proficiency and number of Naval civilians supporting the process and whether improvements in either could affect maintenance duration.

Recommendations for Further Research

In order to manage an activity, you need to measure it and know what is going on. The current approach that the Navy utilizes to conduct major maintenance activities, termed availabilities, for surface ships' situations, makes this very difficult. In order to better manage the maintenance process for surface ships, the Navy and its contractors need to improve their collection and organization of relevant maintenance data. The Navy collects a lot of data, but there are inconsistencies in the data between systems, and some of the data on task durations and each job are highly suspect. The Navy is attempting to address this issue through a new relationship with the Naval Surface Warfare Center, Corona Division to lead the development of the Ship Maintenance Data Improvement Initiative, which is envisioned as a consistent data warehouse. We feel that this is a step in the right direction but note that the data in the warehouse is necessarily dependent on input from shipyards and RMCs. We recommend that better data could be collected if bar coding or some other electronic means were used in the shipyards to track the start and end of each individual job.

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HQMC Aviation (AVN)

NPS-22-M201-B: A Technical Roadmap for Autonomy for Marine Future Vertical Lift (FVL)

Researcher(s): Scot Miller, Bonnie Johnson, Dan Boger, and Christian Fitzpatrick

Student Participation: MAJ Andre Gatlin USA, MAJ David Ray USA, MAJ Calvin Taylor USA, MAJ Scott Drake USA, and MAJ Brian Harrison USA

Project Summary

The United States Marine Corps (USMC) is investing in aviation technologies through its Vertical Takeoff and Landing (VTOL) aircraft program that will enhance mission superiority and warfare dominance. One USMC program initiative is to launch unmanned aerial systems (UAS) from future human-piloted VTOL aircraft for collaborative hybrid (manned and unmanned) missions. This hybrid VTOL-UAS capability will support USMC intelligence, surveillance, and reconnaissance (ISR), electronic warfare (EW), communications relay, and kinetic strike air-to-ground missions.

This capstone project studied the complex human-machine interactions involved in the future hybrid VTOL-UAS capability through model-based systems engineering analysis, coactive design interdependence analysis, and modeling and simulation experimentation. The capstone focused on a strike coordination and reconnaissance (SCAR) mission involving a manned VTOL platform, a VTOL-launched UAS, and a ground control station (GCS). The project produced system requirements and architecture, a conceptual design, and experimental insights into the human-machine teaming aspects of future VTOL capability.

Key findings were that the UAS possesses a high level of digital automation organically and shared with its human partners, which also implies that the humans' planning and execution must be digitally captured. This ensures that the partners will observe, predict, and direct one another, building trust. The second finding was that the entire team requires a secure and redundant primary, alternate, contingency, and emergency (PACE) communications plan to support resilient mission planning, execution, and post-mission analysis. Lastly, the research demonstrated the efficacy of using networked simulators to explore, assess, and measure human machine teaming effectiveness.

The research recommends that the USMC adopt a strategy to procure high-level autonomous UAS, capable of natural language processing, mission assessment, and policy update protocols. Next, continue

assessment of other USMC mission sets when employing VTOL and UAS, using the same techniques. Finally, pursue more distributed simulation for experiments and assessments.

Keywords: *future vertical lift, FVL, human machine teaming, HMT, interdependence analysis, IA, United States Marine Corps, USMC, primary, alternate, contingency, emergency, PACE, digital planning, unmanned air systems, UAS, intelligence, surveillance, reconnaissance, ISR, electronic warfare, EW, strike coordination and reconnaissance, SCAR, vertical takeoff and land, VTOL, observability, predictability, directability, OPD, model-based systems engineering, MBSE*

Background

The USMC seeks to maintain mission superiority and warfare dominance. One pathway toward this goal is through technology advances and the ability to effectively provide innovations to warfighters. The USMC is studying the combination of two innovations (future VTOL helicopters and UAS with different capabilities) to significantly increase mission performance and capabilities. However, the collaboration of future human-piloted helicopters and UAS introduces new complexities for HMT. The USMC needs to better understand the complex HMT interactions among future piloted helicopters that launch and coordinate with future UAS for operational missions, such as the SCAR mission. The USMC needs to determine what mission planning factors must be considered and needs a set of human-machine functional requirements to support future USMC VTOL missions.

The objective of this research was to study HMT challenges and needs for future USMC VTOL-UAS hybrid operations. The research team addressed the following research questions as part of the project:

1. What capacities need to be analyzed between a VTOL, UAS, and GCS in accordance with the functional tasks required to conduct a SCAR mission?
2. How do the following interdependency factors of observability, predictability, and directability influence the HMT relationships between the VTOL, UAS, and GCS?
3. What are the decision-making abilities of an autonomous UAS and what decisions can it make on its own as part of the HMT system?
4. What are the HMT requirements in support of VTOL-UAS hybrid operations for a SCAR mission?

This four-phased research began with a needs analysis, which provided a foundation of understanding and background knowledge to support the analysis in later phases. The team researched key areas of the capstone project including interdependence analysis, HMT characteristics, USMC mission essential tasks, and capacity requirements. The team identified stakeholders and studied stakeholder needs and desires related to the project and mission.

During the Coactive Design Model phase, the team developed an operational view to display the mission scenario and hybrid operational concepts between a VTOL, UAS, and GCS for a SCAR mission. The team performed systems analysis and used the coactive design approach to develop functional tasks and HMT requirements in terms of observability, predictability, and directability (OPD) to display the interdependency relationships between the three systems. The team's interdependency analysis and MBSE artifacts were used to develop a roadmap to drive HMT system requirements using a specific SCAR mission scenario while receiving stakeholder feedback.

In the results generation phase, the team produced analysis results by utilizing the interdependency analysis table of HMT characteristics. The team assessed the results and finalized the project by reporting all results and recommendations obtained using the coactive design and MBSE approaches.

The final phase found the research team working with simulation experts to build an experiment that compared the efficacy of a VTOL platform and independent UAS operating separately versus a hybrid VTOL-UAS human machine team to complete the SCAR mission. This experiment included developing measures of performance and effectiveness for experiment comparison.

Findings and Conclusions

This research aimed to decompose and describe an HMT concept and framework between human operators and UAS' utilizing IA with the goal of constructing a USMC SCAR mission experiment. By combining Coactive Design with systems analysis and MBSE, the research team discovered multiple complex human-machine interdependencies that require significant cognizant input when a human operator is the primary performer. The research also discovered via the IA that the future HMT concept and operational complexity of partnering human operators with machine systems will require substantial analysis and experimentation in order to understand the strengths and vulnerabilities that exist within an HMT system.

This research validates the credibility and applicability of combining the systems engineering framework and Coactive Design process together to decompose and visualize high-level system requirements while also establishing the key interdependencies. This combination enabled HMT interdependencies with direct traceability to high-level system requirements.

This analysis provided the foundation to understand and analyze the primary performer and supporting team member in the execution of a SCAR mission. The IA demonstrates the detailed analysis required in order to understand the complexity of human-machine teams and underpins the criticality of relevant and realistic assumptions within the IA table. Over 86 specific subfunctions were analyzed.

One key takeaway is the assumption that machine systems will possess Level 4 automation, meaning the UAS operates at high automation. This assumption was critical to ensure the HMT concept was adequate to support HMT trust, VTOL cognitive overload concerns, and real-time critical mission decision-making processes.

The research conducted in this capstone provides insights into the development and future application of HMT systems in operational environments. The USMC should continue to invest in the research and development of HMT concepts and continue to refine and construct the HMT relationships in order to understand the complexities of interdependence between humans and machines. For human-machine teaming, the USMC should continue to use the systems engineering framework in conjunction with Coactive Design and IA. This combined approach to system decomposition ensures the appropriate traceability can be achieved within the systems engineering framework and established architecture while also utilizing the benefits of IA to depict human-machine interdependencies. The continued investment in AI and designing AI into future HMT systems will be vital to achieve HMT effectiveness. A deeper understanding of AI and its applicability to future systems should follow the systems engineering approach to enable the visualization of future HMT system concepts.

Two specific recommendations emerge. First, the UAS and the humans must capture their mission planning, execution, and post mission debrief digitally. It is the only common way humans and machines can communicate. An important corollary is that resilient, robust, reliable, and redundant communications channels between the human machine teams are a must.

The final recommendation is that the use of distributed simulation will play a pivotal role in helping the USMC and their partners learn early, fail fast, and accelerate the capabilities of the VTOL family of systems. The sponsor confirmed his continued interest in this approach.

Recommendations for Further Research

The USMC is exploring the use of human-machine teaming to control unmanned aerial systems (UAS) in forward deployed environments across a wide array of mission sets. For USMC hybrid warfare applications to achieve mission superiority and warfare dominance, the USMC needs to understand the human-machine interactions between a VTOL crew and UAS to gain battlespace situational awareness. This research involves a USMC strike and coordination reconnaissance (SCAR) mission in a maritime environment.

The study reviewed the VTOL program, autonomy and automation. It used the coactive design model to explore human-machine teaming interactions and determine interdependencies between the human performer and machine team member using the interdependence analysis (IA) framework based on three factors: observability, predictability, and directability.

Systems analysis supported this method by decomposing the high-level functions of a SCAR mission into hierarchal tasks and subtasks. According to Johnson (2014), the coactive design method exposes interdependencies and uses the IA framework as a design tool. The IA framework captured the interaction between primary and supporting team members to generate HMT requirements by analyzing 17 primary tasks, 33 hierarchical subtasks, and 85 required capacities necessary to conduct a SCAR mission.

Research revealed the need for a robust digital mission planning system that facilitates machine learning, increases in processing power and storage of information on the UAS, and a validated primary, alternate, contingency, and emergency (PACE) communication plan.

To properly assess the HMT requirements, the research team built an exploratory experiment at the Naval Postgraduate School (NPS) Modeling, Virtual Environments, and Simulation (MOVES) laboratory. Measurements were developed to determine HMT effectiveness.

This research provides clear evidence of the complexity of HMT interactions to execute VTOL-UAS hybrid operations during a SCAR mission. The research identifies the need for sophisticated levels of autonomy and technology readiness not currently available. Researchers recommend the USMC continue to study human-machine teaming, with an emphasis on achieving strong automation.

Future work should focus on the initial experimentation of HMT concepts as they apply to current doctrine and multi-domain operations. The use of the NPS MOVES laboratory presents the opportunity to simulate the HMT concept across the domains of air, land, and sea. This opportunity could provide the USMC with relevant and realistic feedback to support the continued refinement of HMT interdependencies and application of systems engineering across future human-machine systems.

More research into the use of digital mission planning systems is needed. This mission planning provides the capability to leverage simulation environments to understand the intricacies of HMT interdependencies while maintaining a cost-effective approach that defines the HMT concept of the future.

As DoD priorities change, the IA studied in this research report must be expanded to encompass multiple future system platforms across the multi-domain environments. The systems engineering process and Coactive Design analysis provide the framework to expound on the HMT concept and move beyond the SCAR mission scenario. Foundational frameworks must be developed that enable the application of HMT across all operations while supporting requirements development.

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HQMC Combat Development and Integration (CD&I)

NPS-22-M255-B: Proliferated LEO Architecture Enabling Beyond Line of Sight Fires (pLEO BLOS Fires)

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Student Participation: LT Marcus Antonellis USN, LT Dylan Bonitz USN, Capt Steven Bourdow USMC, Capt Sokhemalayar Chau USMC, LT Tiara Dienes USN, LCDR Ryan Edem USN, LCDR Brian Kuzara USN, LCDR Bryan Lay USN, Capt Fernando Lopez USN, Capt Amber Luke USMC, LT Christopher Mears USN, LCDR Joseph Miller USN, Maj Liam O'Lone USMC, LT Andre Reich USN, LT Levi Rosa USN, LT Nathan Stuffle USN, and Maj Isaac Williams USMC

Project Summary

The Space Development Agency (SDA) is currently testing and fielding the National Defense Space Architecture (NDSA) which will include hundreds of Earth-orbiting satellites that gather targeting and tracking information and instantly transmit it to warfighters and weapons systems. The architecture includes seven layers: transport, tracking, custody, deterrence, navigation, battle management, and support. This project was centered on efforts towards SDA's transport layer, the layer of data routing, and communications infrastructure. Research focused on development of a space-based transport layer architecture to facilitate beyond line-of-sight (BLOS) communications in support of advanced missile detection, tracking, and long-range targeting. The primary objective of the research was to create a constellation capable of providing assured, resilient, globally persistent BLOS data and communications to warfighters in near real-time while ensuring joint force integration, functionality in degraded environments, and maintenance of low acquisition costs. Mission and system requirements were established and presented to four teams. Modeling using Systems Tool Kit (STK) was performed by each of the four teams to develop a transport layer architecture that met all requirements. An analysis of alternatives was conducted between teams to develop a single final transport architecture. Findings showed that the use of a proliferated low-Earth orbit (pLEO) architecture can benefit the warfighter by providing large throughput, globally persistent, low latency data to large numbers of users, while also maintaining protection from degradation using high-capacity inter-satellite crosslinks. This transport layer can be applied as the backbone and integrator of various space capabilities, including imagery, signals intelligence, tracking, targeting, and communications. It is recommended that this research be expanded upon and included in larger efforts such as SDA's efforts within the NDSA.

Keywords: *beyond line-of-sight, BLOS, global, low latency, Integrated Broadcast System, IBS, National Space Defense Architecture, near real time, proliferated low-Earth orbit, pLEO, persistent, resilient, Space Development Agency, SDA, tactical data links, transport layer, fires, JADC2, NDSA, NOA, overmatch, satellites, space systems*

Background

The recent increase of commercial space-based assets, particularly in low-Earth orbit (LEO), has led towards the adoption of pLEO systems by the national defense industry. Proliferated LEO architectures provide more resilient, globally persistent, and low latency data relay ability, using smaller, less costly satellites than traditional architectures. SDA's system is built on the premise of a threat-driven space architecture, providing different capabilities including surveillance; tracking; targeting; alternate position, navigation, and timing; as well as global battle management support. A pLEO transport layer supports integrating, and delivering high capacity, near real-time data to forces around the world and provides passive resistance to degradation through routable inter-satellite crosslinks and an abundance of satellites, able to maintain operation through disruptive events. Active defenses such as encryption, low probability of intercept/detection, and interference resistance add to the system's security.

Compared to traditional satellite communication methods of large, complex satellites in higher geosynchronous or geostationary (GEO) orbits, LEO satellites have significantly lower latency, cost, and time for development to launch allowing pLEO constellations to be reconstituted cost-effectively every few years, rather than every few decades, meaning constellations will be able to incorporate the latest capabilities and technological improvements.

A market survey was conducted to compile data on each planned system including orbital architectures, technical details of the communications links, system capabilities, expected user experiences, market share, and timelines.

Initial work on this project involved the development and refining of a system mission statement, mission objectives, four overarching mission requirements, and 12 nested system requirements for a nominal SDA transport layer constellation. These requirements were provided to four separate teams of students, each tasked to create and model a unique architecture, proving its ability to meet all requirements, using STK and other available tools and methods.

The team architectures presented included two LEO-only architectures, one LEO architecture with high altitude balloon (HAB) augmentation, and one medium-Earth orbit and highly elliptical orbit hybrid constellation. After an analysis of alternatives between the four team architectures, a final hybrid architecture was developed using the most successful portions of each. The final architecture included a 250-satellite constellation (including 22 on-orbit spares) at 780 km altitude, 84.6-degree inclination, Ka-band downlinks, 60 GHz crosslinks, and capable of HAB augmentation.

This constellation was modeled in STK for analysis of coverage, revisit time, and communications capability at the required frequencies and data rates for downlinks, crosslinks, tactical data links, and IBS support. Coverage and revisit time using STK figures of merit confirmed a 100% persistent global coverage at all latitudes, with no less than two satellites in view at any time. STK link budget analysis showed that user downlinks were successful using Ka-band radio frequency, at a data rate of over 100 Mbps. A radio frequency crosslink of 60 GHz was able to achieve an acceptable level of error at a data rate above 10 Gbps. An analysis of a simulated Link 16 model was also shown to be readily possible with this architecture.

Findings and Conclusions

Overall, utilization of a pLEO architecture, as opposed to a small number of higher altitude satellites, as in traditional architecture, provides a robust passive defense to the degradation of the system. With multiple satellites constantly in view of any ground user, the constellation can retain an acceptable level of operational support even while a large percentage of its satellites are inoperable, due to either intentional or unintentional degradations. With the addition of inter-satellite crosslinks, a pLEO architecture such as this becomes even more resistant to degradations such as uplink jamming, making the system capable of rerouting around interruptions with limited latency increase or loss in system capacity. This analysis reinforces the viability of a pLEO architecture for uses in low latency, resilient, and critical national defense architectures.

This project contributes to pLEO architecture analysis that could be utilized in refining a transport layer for use within NDSA.

Recommendations for Further Research

Future research is recommended to expand upon proliferated low-Earth orbit architectures, filling in technical details, including those that cannot be modeled. For any architecture to be viable, further support from the tech sector will be required. Support for flexible encryption options will be sought from sources such as the National Institute of Standards and Technology (NIST). While NIST standards were explored in this study, it is recommended that an analysis of alternatives of different encryption methods be conducted to determine what standards will best fit the requirements of a national defense architecture.

Furthermore, it is recommended to conduct more research on ground infrastructure necessary to support the National Defense Space Architecture. This model lacks depth in the ground segment and more modeling may optimize ground control stations and reduce program costs. How many ground stations are needed? Where should ground stations be located? What are the policies required to place ground stations outside of the United States?

More research should also be conducted on autonomous systems for command and control (C2). While this research focused on utilizing the Defense Advanced Research Projects Agency's Pit Boss program for proliferated architecture C2, other options were not analyzed. Does Pit Boss satisfy the requirements best?

Are there other options available for autonomous C2 of satellite systems? How do these other autonomous systems compare?

This research was not free from limitations. Computing and processing power available limited analysis of the modeled architecture. Only a handful of sensors, control links, crosslinks, downlinks, ground stations, and users were modeled with the limited power available. Scenarios were additionally analyzed for short durations of time. It is recommended this model be fully built out in a more powerful computing environment, to accommodate a full-scale model with a complete set of satellites, crosslinks, ground stations, and user terminals. This will provide a more realistic model for analysis. Due to the scenario constraints, no analysis was completed to observe long-term effects. It is recommended to conduct an analysis of this model for the entire service life of the spacecrafts to observe perturbations and provide vital insight into station keeping, deorbit timelines, and debris mitigation.

Finally, while this model was created to fit our series of requirements, it has not been fine-tuned; it may not be the most efficient architecture solution and may not be able to meet further undeveloped requirements. It is recommended to look at alternative iterations of proliferated transport architecture for comparison. While four methods were looked at in this study, an endless number of architecture configurations could potentially be utilized. How would this architecture benefit from the use of multiple shells? What other altitudes can be used and what are their benefits? What other inclinations can be used for this architecture? Is there a minimum viable number of satellites to support transport needs or a maximum over which little additional gain is seen?

References

None

HQMC Deputy Commandant Information (DCI)

NPS-22-M344-A: High-Fidelity Digital Twins for Cyber Ops

Researcher(s): Gurminder Singh

Student Participation: Charles Prince CIV, and LT Eric Chamberlin USN

Project Summary
The use of virtualized systems has grown across the application domains that include cyber operator training and offensive and defensive cyber operations. Using virtualized systems is, however, not without its risks, especially if an adversary can determine whether or not a host is virtualized. To prevent such detection, the fidelity of the hypervisor needs to be extended so that adversaries cannot distinguish between a virtualized or a real system. This project is a continuation of our previous work in high-fidelity virtualization (HFV) and HFV artifact mitigation (HFVAM). Previously, we used the Xen hypervisor and DRAKVUF to obfuscate an executable such that the adversary would not know that the system was virtualized. This new work concentrated on the use of a new DRAKVUF capability—process injection by execution—for mitigating HFV artifacts. Our hypothesis was that process injection would lead to even better mitigation of HFV artifacts. We found that process injection was not suitable at this time for mitigating virtualization artifacts, and that DRAKVUF process injection did not work, although the code reported that it had. Thesis research is on-going, including coordination with DRAKVUF developers on the contradictory results that we observed, and updated results should be available by the end of 2022 (Prince, 2022). This project also explored methods for obfuscating the operating system (OS) and libraries to mitigate attack vectors of intelligent malware.

Keywords: *high-fidelity virtualization, HFV, HFV artifact mitigation, HFVAM, Xen, DRAKVUF, process injection, virtual machine, Linux, cloud resilience, web resilience, insider threats*

Background
In recent years, the use of virtualized systems has grown tremendously to include application domains that were originally not envisioned to use virtualized systems. These domains include cyber operator training and offensive and defensive cyber operations. But these domains require certain capabilities in hosts that are beyond what current state-of-the-art hypervisors can support. Additionally, virtualized systems are more vulnerable to attacks when an adversary can determine that the host is virtualized. To support the requirements of these cyber applications, the hypervisor needs to be extended with advanced capabilities, leading to HFV. To prevent the detection of virtualized systems, we need to mitigate artifacts

of virtualization. This work and area of study will be beneficial to cyber operations, as well as cloud resiliency and web resiliency, and may expose and perhaps prevent external and insider attacks.

The objective of this project was to make an attacker believe that a system is not a virtual machine, when in reality that system is running as a virtual machine. The reasons to do this are various. An intelligent malware munition (or in general, an attacker) may detect what kind of Linux system is running and choose an attack vector based on what the malware detects. If the malware misdiagnoses the system, then the attack may fail and lead to exposing that malware to system defenders.

This work is a continuation of previous work (Norine, 2020) that used DRAKVUF to relabel the path of an executable process to that of another executable in order to deceive the attacker. This relabeling technique provided results to lead the attacker into believing that they had gained access onto a non-virtualized “bare metal” system. This work tried to extend the previous work by injecting the executable with spoofed information in such a way that the attacker could not determine what had happened.

Accomplishing this mitigation is difficult in that it requires direct manipulation of the Linux kernel and the corresponding data structures. The Linux kernel has become progressively harder to decompose, or even to determine what happens in a system call. Another layer of difficulty occurs when considering shellcode.

Findings and Conclusions

This research found that the DRAKVUF process-injection using execution (DPIE) was not currently suitable for HFVAM. DPIE could not affect standard output, nor could it overwrite an output file, even though the module believed that the injection had taken place. However, the DRAKVUF process-injection using shellcode (DPIS) may be able to support HFVAM. The DPIS is based on *vdso*, which is a kernel function and not a system call, making it more difficult for an attacker to recognize that HFVAM is taking place. In addition, this research revealed that HFVAM of OS and library versions may well lead smart malware munitions and attackers to be fooled in exposing themselves, thus preventing attacks.

The short-term implications of this research indicate that process injection is not suitable at this time for mitigating virtualization artifacts. However, our findings showed that it may be used for deceiving malware's perception of the OS and library versions, which suggest that in the long-term, continued research is warranted despite the null hypothesis observed in DRAKVUF process injection.

Recommendations for Further Research

The DRAKVUF process-injection using shellcode (DPIS) method appears to be a good candidate for use in high-fidelity virtual machine artifact mitigation (HFVAM) because that module's method is based on *vdso*, a hard-to-track kernel function. DPIS could be designed to jump to an area of code where it can run another executable, outputting the results to standard output (i.e., the display) or to an external file. Another area of further research is using HFVAM for operating system and library versions as a way to extend resilience for smart malware munitions as well as attackers. Another area of future research should be micro-kernel extensions to Xen in order to provide greater resilience to the hypervisor itself.

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HQMC Installations and Logistics (I&L)

NPS-22-M273-A: Condition-Based Maintenance Implementation and Potential in USMC Ground Transport

Researcher(s): Eva Regnier, and Bryan Hudgens

Student Participation: Capt Mitchell Stuetelberg USMC, Maj Jonathan Thomas USMC, Maj Brian Harding USMC, and Maj Liston Pennigton USMC

Project Summary

The Marine Corps is undergoing organizational change efforts to integrate Condition-Based Maintenance Plus (CBM+) as a maintenance strategy to support ground equipment across the enterprise. We studied the implementation of CBM in industry and identified common themes, including guidelines for identifying platforms most suited to CBM—those that are critical and costly to replace. We studied people and processes for implementation of CBM+ and identified critical barriers including incompatibility among policies.

Existing tools within the Marine Corps policy refinement process, such as the Total Life Cycle Management Cross Functional Team, can be used to establish a CBM+ guiding coalition. We recommend creating an environment that fosters short-term wins through interim exceptions to policy and consolidating these gains in a single volumized maintenance order. The Field Supply and Maintenance Analysis Office can be utilized as a key contributor in communicating and enabling the CBM+ vision for Marine Corps maintenance through evaluating, training, and consolidating best practices of CBM+ processes. This further supports the current Commandant's priority initiatives, both Force Design 2030 and Talent Management 2030. Reducing unnecessary maintenance actions and cross-functional training will support both retention and development of high-performing Marines.

Stuetelberg and Thomas briefed their work to BGen. Chalkley, then at Headquarters Marine Corps Installations and Logistics, and currently Commander of 3rd Marine Logistics Group (3d MLG). Their report was also sent to the Secretary of the Navy's Chief of Staff, the Honorable Tommy Ross. During a guest lecture in a Naval Postgraduate School (NPS) logistics capstone course, the Honorable Mr. Ross specifically identified their topic as a great example of "key" topics (direct quote). Harding and Pennington briefed senior leaders including Maj. Gen. Maxwell, at the time Vice Director for Logistics, Joint Staff, and now Assistant Deputy Commandant, Installations & Logistics (Facilities).

Keywords: *condition-based maintenance, logistics, USMC, private sector, best practices, metrics, expeditionary logistics, decision analysis, decision support*

Background

The Marine Corps is undergoing organizational change efforts to integrate CBM+ as a maintenance strategy to support ground equipment across the enterprise. Currently, the Marine Corps uses a traditional time-based strategy for ground equipment maintenance, conducting preventative maintenance at specified time intervals and corrective maintenance when failure occurs. CBM+ will generate increased cost-savings, reduce man-hour requirements, and improve operational availability for Marine Corps' ground systems.

CBM has already been widely adopted in industry for several decades. We reviewed the literature on CBM and interviewed maintenance professionals in the mining, railroad, and heavy equipment industries to learn about their implementation strategies, challenges and lessons learned. Using a case study methodology, we synthesized themes on best practices. We evaluated the applicability of their experiences in the context of Marine Corps ground systems maintenance and developed findings and recommendations for the implementation of CBM+ sensors and data analytics in the Marine Corps.

The three pillars of CBM+ are people, processes, and technology (Headquarters Marine Corps, 2020). During this project, the Marine Corps stood up a Program Office for CBM+ which is addressing the technology portion of the transition. To identify gaps in the Marine Corps' organization-wide policies, processes, and personnel to be technology-empowered and data-driven in its maintenance strategies, we conducted a second phase of the research.

To identify gaps in the Marine Corps, we reviewed ground maintenance policies considering prior findings on CBM implementation and the organizational change literature. We interviewed fifteen military and civilian ground maintenance subject matter experts in key roles in the organization. Based on the information collected, we identified barriers to and opportunities for change within the Marine Corps ground maintenance community, and further recommendations for CBM+ implementation.

Findings and Conclusions

In industry, CBM is heavily predicated on collecting and analyzing data. Companies that are successful with this strategy all possess an internal data analytics department staffed with specialized professionals in this field. Moreover, data analysis was enabled by effective and interoperable software and hardware suites. Neither of these is readily achievable given current Marine Corps maintenance manpower structure and limitations on available technology and data security requirements. CBM is not one size fits all. CBM implementation should prioritize costly pieces of equipment, low- density assets that are crucial to revenue-producing activities, or equipment where unplanned mechanical failure presented significant worker safety risks.

Four organizational barriers to CBM+ emerged from our interviews with Marine Corps subject-matter experts. First, there is a lack of clear and consistent understanding of CBM+ across the Fleet Marine Force. Second, there is conflict among various orders and policies that delineate Marine Corps maintenance strategy, and many legacy policies directly conflict with CBM+ strategies. Third, inspections heavily influence maintenance actions at the operational unit level and hinder implementation of CBM+ initiatives. Finally, competing priorities reduce focus and capacity necessary to change maintenance strategies.

Our primary recommendations for improving CBM+ implementation are focused on aligning the effort with other enterprise priorities and aligning policies to permit and support innovation in implementing CBM+. We recommend creating an environment that fosters short-term wins through interim exceptions to policy and consolidate these gains in a single volumized maintenance order. Operational units need to be empowered to seek out process improvements and opportunities to apply CBM+ practices. The Field Supply and Maintenance Analysis Office can be utilized as a key contributor in communicating and enabling the CBM+ vision for Marine Corps maintenance through evaluating, training, and consolidating best practices of CBM+ processes.

Existing tools within the Marine Corps policy refinement process, such as the Total Life Cycle Management Cross Functional Team model, can be used to establish a CBM+ guiding coalition. A CBM+ guiding coalition would guide, coordinate, and communicate CBM+ implementation throughout the Marine Corps, including communicating to the Fleet Marine Forces how CBM+ supports the current Commandant's priority initiatives, both Force Design 2030 and Talent Management 2030. Reducing unnecessary maintenance actions and cross-functional training will support both retention and development of high-performing Marines, with agility and resilience to operate in challenging operational environments.

Recommendations for Further Research

The Condition-Based Maintenance Plus (CBM+) implementation is moving forward. The Marine Corps stood up a new program office for CBM+ which is addressing the technology portion of the transition, while 3rd Marine Logistics Group (3d MLG), under the command of BGen. Chalkley, was briefed on the first phase of our research. 3d MLG completed a one-year pilot of CBM process-level innovation (3d MLG, 2022). The research team has been in regular correspondence with Headquarters Marine Corps Installations and Logistics regarding our findings and recommendations with respect to people and processes. No additional research following on this project has been identified. We have transitioned the results to the fleet.

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HQMC Manpower and Reserve Affairs (M&RA)

NPS-22-M205-A: M&RA Manpower Models Modernization

Researcher(s): Chad Seagren, Arijit Das, Marigee Bacolod, and Daniel Reich

Student Participation: Maj Aaron Falk USMC

Project Summary
In his planning guidance, the Commandant states "We will ... accelerate our transformation from disconnected legacy systems to an integrated data architecture that treats data as it should be –a critical resource" (Berger, 2019, p. 15). This project is a bold step in support of that transformation for Manpower & Reserve Affairs (M&RA), which possesses numerous mathematical models that support the management of the human resources development process (HRDP). Our approach demonstrates how M&RA can leverage the latest technology in data architecture and decision support models to overcome these deficiencies. We formulate modernized versions of models to fill the roles currently held by the Total Force Planning Model (TFPM) and the Enlisted End-Strength Planning Model (ESPM). In addition, we formulate a discrete event simulation model to analyze changes in structure that currently has no legacy counterpart. We successfully replicated the TFPM in Python and identified a number of improvements that should be made with respect to data formatting. An inability to obtain sufficiently accurate separation data prevents progress towards replication of the ESPM. Finally, we successfully implemented a discrete event simulation of the manpower system. While initial validation attempts appear favorable, a more complete validation is prevented by the same inability to obtain appropriate data.

Keywords: *United States Marine Corps, USMC manpower planning, human resources development process, decision support, operations research, total force planning model, enlisted end-strength planning model, machine learning, discrete event simulation*

Background
In his planning guidance, the Commandant states "We will ... accelerate our transformation from disconnected legacy systems to an integrated data architecture that treats data as it should be –a critical resource" (Berger, 2019, p.15). This project is a bold step in support of that transformation for M&RA, which possesses numerous mathematical models that support the management of the HRDP. In general, these models suffer from the following limitations:

a) Models tend to be implemented in an outdated computational language.
b) Models tend to require substantial human intervention to manage the interface between models, as when the product of one model is a required input for another model in the process.
c) Models tend to require substantial human intervention to manage the interface between the model and sources of empirical data such as Total Force Data Warehouse (TFDW).
d) Models tend to lack standardization with respect to elements common among models. For example, several models might require an estimate of the attrition rate for, say, Marines of a particular rank and occupational specialty, yet each model might contain a differently calculated rate.

In addition, some processes within the HRDP lack any sort of decision support tool, but could benefit from the addition of such a tool, provided it is sufficiently user friendly and sufficiently interoperable with other models and data sources.

Our approach demonstrates how M&RA can leverage the latest technology in data architecture and decision support models to overcome these deficiencies. We focus on the following three lines of effort (LOEs).

LOE 1: Formulate a model that fills the role in the HRDP that the legacy Total Force Planning Model currently fills. Given the Authorized Strength Report and various budgetary and policy constraints as inputs, this model produces an ideal inventory by grade and military occupational specialty (MOS) for the present fiscal year and six future years. We provide analysis as to the feasibility of implementing such a model in Python as well as the benefits such a model could bestow. In addition, we consider ways to make the model more capable and more user-friendly than the legacy TFPM.

LOE 2: Formulate a predictive machine-learning-based model that fills the role in the HRDP that the legacy Enlisted End-Strength Planning Model (ESPM) currently fills. Given historical attrition behavior and the planned accession mission, this model provides a within-execution-year forecast to determine the likelihood that the system will meet the target enlisted end-strength at the end of the fiscal year.

LOE 3: Formulate a discrete event simulation model to assist in the analysis of changes in the structure of a given Occupational Field (OccFld). Given a notional target inventory for that OccFld; the current inventory for that OccFld; historic attrition behavior; and the relevant Enlisted Career Force Controls; this model produces an estimate of the resultant promotion timing for each grade, as well as an estimate of the feasibility of obtaining the desired inventory levels. We provide an analysis of the feasibility of implementing such a model in Java.

Findings and Conclusions

LOE 1: We successfully implemented a replication of the TFPM for officers in Python using a parallel processing approach. We processed all 257 combinations of MOS and officer type with FY22 data and compared those against the official TFPM outputs and produced identical results in 244 out of 257 cases. The other 13 instances contained discrepancies that were reviewed by a domain expert. Some discrepancies were caused by manual adjustments and others were categorized as errors. We provide detailed recommendations for improvements in four key areas. We identify significant disadvantages with the data formats we received, including inconsistent field naming conventions from one data table to another, and implicit representations that are understandable to a human analyst but insufficient for machine processing. These data formatting deficiencies increase the complexity of logic and code required for generating the TFPM.

LOE 2: We assess the legacy ESPM and formulate a predictive machine-learning-based ESPM. We had hoped to estimate this model to illustrate its feasibility in replacing the legacy model. Unfortunately, we encountered extreme challenges collecting the necessary data. As of the writing of this report, we are still awaiting key data elements in order to estimate this model. The model and results will be part of the FY23 study, beginning with Major Aaron Falk's March 2023 thesis.

LOE 3: We successfully formulated and implemented a discrete event simulation model of the manpower system in Java. Given a notional target inventory for an OccFld, the current inventory for that OccFld, historic attrition behavior, and the relevant Enlisted Career Force Controls, the model provides estimates of expected promotion timing for each grade, expected accession mission, and expected retention requirements. The model easily employs data-farming techniques and lends itself to both transient and steady-state analyses. While initial validation attempts demonstrate that the model appears to perform well, this aspect of the project was plagued with the same data collection issues as LOE 2, and much less time was available for validation. Therefore, we recommend to continue the validation efforts into the future, both with respect to additional target years and additional communities and MOSs. Researchers should confirm the existence of proper time to promote data as well as empirical retention data. It is likely that minor refinements to the manner in which Marines in the above-zone for promotion are managed, as well as minor refinements to how reenlisted Marines are distributed across grades will prove worthwhile and improve model performance.

Ultimately, the most important finding of this project is that the records contained in TFDW might be insufficient to support building a rigorous mathematical model of attrition behavior. Namely, the reason for a Marine's separation from active duty does not appear to be properly archived. The Marine Corps will fail in its efforts to transform from an industrial age organization to an information age organization if the data it relies on to make the most elementary manpower management decisions (i.e. the effort to make end-strength) is flawed or non-existent.

Recommendations for Further Research

First, the Marine Corps should make steps to ensure that the reason(s) that a Marine separates from active duty is properly archived and is easily retrievable for purposes of analysis. The difficulty in collecting this and other relevant data prevented any real progress towards replication of the Enlisted End-strength

Planning Model (ESPM) (line of effort [LOE] 2) and hampered validation efforts of the model we analyze in LOE 3. Given this lack of progress, we recommend continuing work on the ESPM.

Upon conclusion of Aaron Falk's March 2023 thesis, the model he develops and analyzes in that thesis will be delivered to Manpower & Reserve Affairs (M&RA). Due to statutory restrictions on the appropriate uses of Navy Research Program funding, the other models we analyze in this project cannot be delivered. We recommend M&RA seeks other channels to replicate this research and develop models that can be lawfully delivered and implemented.

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HQMC Plans, Policies & Operations (PP&O)

NPS-22-M342-A: Assess Intermediate Force Capabilities (IFC) and concept of operations for application during the Competition Phase in an environment of GPC

Researcher(s): Robert Burks, Lyla Englehorn, Marianna Jones, Jeffrey Kline, and Jeffrey Appleget

Student Participation: MAJ Caleb Edwards USA, MAJ James Raub USA, MAJ Marc Rose USA, MAJ Augustin Paulo USA, CDR Milton Mendieta Ecuador Navy, Capt Chad Minnick USAF, LT Luke Goorsky USN, Maj Andrew Mirsch USMC, LT Young Hong USN, Capt Tyler Goble USMC, Capt Benjamin Cohen USMC, LT Steven Domingo USN, CPT Patrick Foley USA, LCDR Konstantinos Meligkaris Hellenic Navy, MAJ Michael Rowen USA, LT Brandon Schultz USN, LT Lauren Breuer USN, MAJ Devin Kirkwood USA, LT Jiles Maness USN, LTJG Christopher Mears USN, Maj Dustin Merritt USAF, MSgt David Nass USMC, MAJ LaMarke Patterson USA, MAJ Mareks Runts Latvia SOF, MAJ Joseph Simon USA, Maj Zachary Finch USMC, MAJ Thomas Kraus USA, LT Ryan Satanek USN, LTC Matthias Schwarzbauer German Army, CPT Kenny Teo Singapore Army, and MAJ Michael Tovo USA

Project Summary

This research examines the potential effects of a set of intermediate force capabilities (IFC) to assess their strategic impact on a near-peer adversary during the competition phase. The effort attempts to gain insights and identify challenges to the employment of IFCs through several venues. Leveraging our defense analysis and operations research department faculty and students, this project conducted a workshop and analytical wargame to capture challenges and opportunities in a plausible great power competition (GPC) "gray zone" scenario. Wargaming assessed potential concepts for Special Operations Forces (SOF) employment of a set of IFC, emerging IFC concepts and technologies, and their implications for operations across the competition continuum.

The research leveraged the Naval Postgraduate School (NPS) Warfare Innovation Continuum (WIC) and multiple Joint Campaign Analysis (JCA) and Wargaming Applications courses to develop its insights.

The primary focus of the effort was to determine the operational utility of IFCs for SOF to attain and maintain a position of advantage in the grey zone while deterring lethal conflict escalation. The effort was based on an exchange of ideas between the Joint Intermediate Force Capabilities Office (JIFCO) and NPS researchers to better understand current operational concepts and concerns, and identified two critical JIFCO issues for exploration. The research effort identified that IFCs do have the potential to provide

utility to SOF to maintain an advantage in the gray zone, while countering lethal conflict and the risk of using IFCs is not significantly more than the risk associated with the current conduct of SOF doctrinal tasks. However, there are some caveats concerning the perceptions of risk associated with IFCs that may constrain their application.

Keywords: *intermediate force capabilities, IFC, great power competition, GPC, wargaming, joint campaign analysis, gray zone, hybrid warfare, Joint Intermediate Force Capabilities Office, JIFCO*

Background

Intermediate force capabilities provide options that enable the warfighter to seize or regain the initiative in confrontational situations where potential adversaries appear to be demonstrating malign behavior. In these situations, IFCs may be appropriate, proportional responses to acts that may appear hostile, but fall short of acts or behaviors justifying the use of deadly force. IFCs represent a strategic risk mitigation investment that are designed to provide our warfighters tools to compete below the level of armed conflict without losing credibility in the information space. The lack of IFC puts the United States in a position of having to accept malign behavior to the point which it becomes "fait accompli" for peer adversarial expansionist objectives. IFCs are intrinsic in their ability to dissuade malign behavior and impose costs on near peer adversaries while minimizing collateral damage to infrastructure and permanent injury to personnel.

The wargames utilized in this work familiarized participants and observers with both IFCs and concepts for employment. Under the NPS WIC construct, an NPS student mini-study team, conducted in the JCA course, informed and underpinned the design and conduct of further research into our research's two critical JIFCO issues. This mini-study was followed by an NPS faculty-advised student wargaming team in the Wargaming Applications course, that designed, developed, conducted, and analyzed a wargame leveraging the findings from the mini-study. The wargames modeled SOF utilization of IFCs in a South China Sea scenario to best posture SOF to deter escalation of events.

The overarching objective of this effort was to determine the operational utility of IFCs for SOF to attain and maintain a position of advantage in the grey zone while deterring lethal conflict escalation.

This effort focused on gaining insights into the following two major issues:

1. What utility do IFCs provide SOF to maintain advantage in the grey zone?
2. What are the risks of using IFCs?

Findings and Conclusions

This effort resulted in the following findings and conclusions for each identified issue.

Issue 1: IFCs do have the potential to provide utility to SOF to maintain an advantage in the gray zone while countering lethal conflict. When appropriately used, IFCs leverage technology to offer SOF increased options to confront adversaries, both state and non-state, and influence malign behavior in low-intensity conflicts or in conflicts below the threshold of violence. The proper use of IFCs hinges upon training, education, dissemination, permissions, and authorities. Furthermore, understanding the operational environment is crucial to ensure the effective use of IFCs and to understand the second and third order effects of potential proliferation of IFCs to host nation or partner forces. Several factors affect the utility of individual IFCs for SOF. These factors include, but are not limited to size, range, platform modularity, simplicity, deniability, and security classification.

Issue 2: The risk of using IFCs is not significantly more than the risk associated with the current conduct of SOF doctrinal tasks. However, there are some caveats concerning the perceptions of risk associated with IFCs that may constrain their application.

The greatest risk of using IFCs is the inability to prevent poor media interactions or malign adversary narratives from creating a counter-productive response that actually increases the risk of violent confrontation or increases the difficulty of accomplishing friendly force objectives.

A lack of education concerning IFCs among the leadership and staff of the Theater Special Operations Commands, coupled with underwhelming risk mitigation methods and the potential for massive negative blowback in the information space reduces the likelihood of tactical SOF elements gaining the necessary permissions from senior commanders to utilize IFCs in the field.

JIFCO should pursue a two-pronged approach for advocating the use of IFCs in SOF. They should approach technical integration support companies with the technology and the Theater Special Operations Commands with recommendations for doctrine, policy, and integrating the advanced technology IFCs JIFCO can provide.

Recommendations for Further Research

The intermediate force capabilities and potential employment mechanisms are still nascent concepts that require further research to better understand how the special operations forces (SOF) community can use them to operate more effectively to establish a position of advantage, while preventing the escalation of violence. Essentially, these employment mechanisms will need to mature through continued programs of wargaming and campaign analysis research to best serve joint intermediate force capabilities office and the SOF community.

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None

NPS-22-M359-A: Extending Cognitive Assistance with AI Courses of Action

Researcher(s): Sharon Runde, and Arkady Godin

Student Participation: No students participated in this research project.

Project Summary

In the United States Marine Corps (USMC) Fire Support Coordination Unit (FSCU), the FSCU officer often does not have the correct, optimal information for situational awareness (SA) and, as a result, can make poor decisions in the battlefield. This is a problem because it leads to fratricide and unintended civilian casualties. The working research question is, to what degree will situational awareness and decision quality improve by using a cognitive agent that reduces friction factors in knowledge flows? A factorial, quasi-experimental design will be implemented as described by Kerlinger and Lee (2000). Quantitative methods will be used to analyze data collected on the variables to show a corollary relationship between the use of a cognitive agent and the resulting improved situational awareness and decision quality versus without the use of a cognitive agent. This research explored the availability of potentially existing cognitive agents that could provide situational awareness and context to an operator in an operational military environment. While there is active research ongoing in this area, a cognitive agent has yet to be designed and developed to meet this need. Since such a tool does not yet exist, it is recommended that this line of research continue so that the described discovery experiment plan can be executed. By continuing this research, a baseline of experimentation can provide insights into how a technology may be designed and developed with various artificial intelligence/machine learning (AI/ML) algorithms. Future research beyond the exploratory and discovery phases could look at how a cognitive agent could provide courses of action based on all data sources available. Further, a cognitive assistant (CA) with the ability to provide courses of action would shift from 'human-in-the-loop' to 'human-on-the-loop,' thereby reducing cognitive load.

Keywords: *human-machine teaming, HMT, mission workflows, automation, machine learning, ML, artificial intelligence, AI, courses of action, COA, wargaming, decision making, naturalistic decision making, NDM*

Background

This research examined automating tactical workflow tasks optimized in complex, interdependent missions and joint activities. In 2012, the Defense Science Board Task Force Report: The Role of Autonomy in DOD Systems, stated, "the true value of [autonomous systems] is not to provide a direct human replacement, but rather to extend and complement human capability by providing potentially unlimited persistent capabilities, reducing human exposure to life threatening tasks, and with proper design, reducing the high cognitive load currently placed on operators/supervisors" (p. 1). Furthermore, the 2018 DOD Artificial Intelligence Strategy identifies delivery of AI-enabled capabilities that includes "improving situational awareness and decision-making…by offloading tedious cognitive or physical tasks and introducing new ways of working" (p. 7).

Several United States Marine Corps (USMC) thesis students studied how to design interdependent human-machine teaming (HMT) for military applications (Beierl & Tschirley, 2017; Clarke & Knudson, 2018). In Capt. Ben Herbold's thesis (2020), he continued this research and studied interdependence analysis matrix using the approach developed by Dr. Matt Johnson at IHMC (2014). The current research was based on the Plans, Policy, & Operations (PP&O) United States Marine Corps, Headquarters (USMC HQ). Studies from PP&O USMC HQ have laid the groundwork that directly supports the mission of the Headquarters Marine Corps (HQMC) PP&O for "coordinating the development and execution of service plans and policies" for joint and service functions (Headquarters Marine Corps, n.d.).
Previous research has been computationally intensive and unavailable at the tactical edge. Currently, humans drive intelligent tasks, and the machine performs simple, programmable, mundane tasks. While programming improves task efficiencies at the margin, HMT activities need to be extended to reduce the cognitive load of operators in a complex and dynamic operational environment. An HMT cognitive assistant should reflect realistic environments such as multiple agents, human and/or computer. As noted by Stilman (2000), "None of the conventional approaches … allow us to scale up to the real-world concurrent systems with respect to the number of agents, dynamic change of their capabilities, size, shape, and dimension of the operational district, concurrent actions, real time requirements, etc." (p. 8). As AI advances, machine intelligence grows, resulting in humans realizing that machines may become true peers to humans in conducting enriching dialogue via an HMT interface.

We studied the HMT interface with an AI tool, providing SA. We believe humans should learn from intelligent AI agents. Learning from AI agents results in reduced decision-making errors, due to humans progressing in a temporal dimension by learning tacit knowledge of SA from intelligent AI agents. Our research results expect to support that bringing congruency into the HMT interface translates into decision superiority as human decision making is aligned with a superior, AI enabled decision support system.

This research aids the USMC PP&O in accomplishing the "development and articulation of concepts, plans, and policies to support the Joint Strategic Planning System" by laying the groundwork for AI decision support in reducing cognitive load on operators (Headquarters Marine Corps, n.d., Functions section).

Findings and Conclusions

This research explored the availability of potentially existing cognitive agents that could provide situational awareness and context to an operator in an operational military environment. While there is active research ongoing in this area, a cognitive agent has yet to be designed and developed to meet this need.

A factorial, discovery, quasi-experimental design will be implemented as described by Kerlinger and Lee (2000). As discussed by Runde (2016), discovery experiments can be very economical because they do not employ large amounts of infrastructure and resources (p. 27). Discovery experiments are an important element in the experimentation process as some ideas may fail early on. These failures, however, provide a rich learning source prior to investing resources.

Discovery experiments may be successful, yet further discovery testing may continue to be explored to validate findings, refine concepts, and determine the best fit for implementation (Alberts, 2009). Quantitative methods will be used to analyze data collected on the variables to show a relationship between the use of a cognitive agent and improved situational awareness and decision quality versus without the use of a cognitive agent. The design will be 'quasi-experimental' because it may not be possible to have more than one group that receives the experimental treatment, and the other group would not receive the experimental treatment (Kerlinger & Lee, 2000). The training scenario will be provided by the Army through an existing program called Scarlet Dragon. Todd South cites Lt. Gen. Erik Kurilla, XVIII Airborne Corps commander, who describes Scarlet Dragon as a series "designed to increase our joint warfighting capability and how AI-augmented decision making significantly increases the scale, speed and accuracy of our targeting process" (South, 2021, para. 15). The availability of this training series is an ideal match for this research study due to its focus on AI within the Navy and joint forces.

Recommendations for Further Research

Since an artificial intelligence (AI) tool does not yet exist, it is recommended that this line of research continue so that the described discovery experiment plan can be executed. By continuing this research, a baseline of experimentation can provide insights into how a technology may be designed and developed with various AI/machine learning algorithms. Future research beyond the exploratory and discovery phases could look at how a cognitive agent could provide courses of action based on all data sources available. Further, a cognitive assistant with the ability to provide courses of action would shift from 'human-in-the-loop' to 'human-on-the-loop' thereby, reducing cognitive load.

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HQMC Programs & Resources (P&R)

NPS-22-M131-A: Equipment and Supply Readiness

Researcher(s): Bryan O'Halloran, Harrison Schramm, and Raleigh Durham

Student Participation: Aiden Keene, Alvaro Vasquez, and Lara Yaroszewski

Project Summary

Headquarters Marine Corps, Programs and Resources, Marine Corps Systems Command, and Fleet Marine Forces desire a model that will enhance the understanding of the equipment readiness issues and needs experienced with the Secure, Mobile, Anti-Jam, Reliable, Tactical Terminal (SMART-T) and Joint Light Tactical Vehicle (JLTV) programs. Equipment maintenance information coupled with the model will provide insight into different resource allocation options available to improve the readiness of these systems. This knowledge will aid in decisions for which resources are applied to improve equipment readiness.

The systems engineering capstone team developed a step-wise model to input equipment maintenance data, transform the data to a useable state, perform categorical analysis, and conduct equipment cost analysis. To foster the data-driven model, equipment maintenance data was provided to the systems engineering capstone team for both the SMART-T and JLTV systems. The maintenance data spanned multiple years for each system and included 42 unique fields associated with each maintenance record. This data-driven approach to develop the model allowed for several types of analysis to be performed on the data sets.

Overall, the model developed provides the ability to visualize maintenance rates based on primary defect codes which can alert analysts to changes in expected or historical maintenance rates. These changes could be a sign of future problems and enable the Marine Corps to act prior to these potential issues develop into a problem with a significant impact. The model can also predict future maintenance needs which can be used to allocate resources appropriately to handle the expected maintenance load.

Keywords: *readiness, maintenance modeling, maintenance analysis, data analysis, cost analysis, ground vehicles, data modeling, data visualization, maintenance predictions, program planning, resource planning, resource allocation*

Background

The readiness of equipment plays a key role in the overall mission readiness for Marine Corps units. The May 2014 *Commander's Readiness Handbook* outlines a framework that the United States Marine Corps

(USMC) uses to better understand and improve unit and joint level readiness to achieve an overall improved level of readiness. One aspect of determining unit level readiness is the operational condition of the mission-essential equipment at a given unit needed to meet its mission. Several factors could impact the readiness of a given system, including the amount of time it takes for a system to traverse through the maintenance process. Two systems of interest for this study are the SMART-T and the JLTV, which are critical systems the USMC uses to enable and conduct missions.

The concept of improving mission readiness by improving operational availability or equipment readiness was present in the literature reviewed aligning with the general concept of this study, to increase Marine Corps Unit mission readiness by improving equipment readiness. These research efforts either focused on a single system, such as developing a decision model for the MK-16 Mine Countermeasure System (O'Rourke, 1997), or focused on a specific process, the calibration process (Bevel et al., 2006), and its effects on operational availability of supporting equipment. While the budget forecasting study (Dahel, 2019) did show the ability to use historical data to predict monthly maintenance costs for unscheduled maintenance, the study focused solely on cost for corrective maintenance. None of these previous studies looked at the effects of resource allocation to provide decision support for where resources could be best allocated to improve the mission readiness of a particular system.

This project will work to mitigate these systems' readiness concerns by developing a Resource and Equipment Readiness model. The desired product is a model that will improve the understanding of where resources can be best allocated to realize the largest increase in mission readiness for the system. The model will accomplish this by identifying issues that will require resources, forecasting the optimal levels for maintenance resource allocation in the near term, and to potentially predict the upcoming need to provide and upgrade or field a replacement based on failure deviations. The model will also provide the ability to visualize cost data in a manner that will help inform where allocation of funds could be best applied. These forecasting and predicting capabilities can provide insight for program offices to use to increase their equipment readiness ratings and overall unit mission readiness.

Findings and Conclusions

Equipment readiness is a major part of a unit's mission readiness. Allocating resources could influence a system's ability to efficiently traverse through the maintenance process. This study focused on developing a data-driven model to analyze maintenance data and show maintenance trends, based on the initiation of a service request and the associated operational status and primary defect codes. The model developed can show maintenance initiation trends for the categories that were specifically selected; however, categorizing the data differently or analyzing all possible categories would lead to more information being provided to decision makers. The team selected the top occurring defects for this analysis to ensure a good analysis was conducted.

Overall, the model developed provides the ability to visualize maintenance rates based on primary defect codes which can alert analysts to changes in expected or historical maintenance rates. These changes could be a sign of future problems and enable the Marine Corps to act prior to these potential issues developing into a problem with a significant impact. The model can also predict future maintenance needs which can be used to allocate resources appropriately to handle the expected maintenance load.

The results of this analysis are very promising, showing potential to predict future maintenance needs and inform where resources can be best allocated to achieve a goal. The results can be used to predict maintenance rates and forecast trends, as well as provide insight for warning thresholds where maintenance resources should be applied. Also, the initial results of the cost analysis show potential to integrate maintenance cost information into this predictive analysis enabling the model to forecast maintenance costs along with the maintenance rates. This model was developed using maintenance data for a vehicle and should be applicable to any vehicle-based system. However, prior to considering this work to a new system, we recommend that the sponsor conduct an in-house verification by using the model to predict future maintenance actions and verify the model's effectiveness.

Recommendations for Further Research

Through development of the data-driven model, it was found that there were some areas of interest that the systems engineering capstone team was not able to study that would potentially have an impact on predicting when and where resources should be allocated. This study looked at maintenance initiations over time to discover trends and predict future maintenance needs as well as identify changes in maintenance patterns that could lead to larger issues. Some data that was not available was mileage stamped data for the two vehicles being studied. Understanding how mileage on a vehicle affects maintenance needs and how this can inform resource allocation would be of value.

The visualizations presented in this study were not all encompassing. The dataset provided has the potential to be visualized in several diverse ways depending on what information is desired. To get more information out of the data, the data will need to be cleaned and categorized differently to enable different viewpoints. Some examples of other visualizations would include visualizing the amount of time a system spends in the maintenance cycle per service request number, or the amount of time an item spends idle in the maintenance cycle due to being short technicians, short parts, or some other reason. Both of these coupled with analysis like that conducted in this study would provide views that could inform where resources may be best allocated to achieve an increase in mission and equipment readiness. These examples also have the potential to identify inefficiencies in the maintenance process that could be addressed by adjusting how resources are allocated.

A limitation to the approach provided in this project is that assessing historical maintenance data is inherently a reactive approach to identifying issues. This can quickly lead to insurmountable issues for resource planning because it pressures the supply chain and results in long lead times for parts. As such, we recommend a follow-on study to assess condition-based maintenance (CBM) data for the Joint Light Tactical Vehicle (JLTV) with the goal being to identify data signatures that indicate imminent failure. By the end of FY22, the JLTV program had installed CBM sensors on roughly 200 vehicles and has collected a significant amount of usable data.

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Marine Corps Forces Command (COMMARFORCOM)

NPS-22-M337-A: SOF-MAGTF Capabilities Integrations Analysis and Operational Modeling (Continuation)

Researcher(s): Robert Burks, Jeffrey Kline, Marianna Jones, and Jeffrey Appleget

Student Participation: MAJ Ryan Gauntt USAF, David Nass USMC, Maj Mareks Runts, Maj Anitti Heinola, Capt Alex Fisher USMC, Capt Wei Ting Goh, MAJ Caleb Edwards USA, MAJ James Raub USA, MAJ Marc Rose USA, Maj Andrew Mirsch USMC, LT Young Hong USN, and Capt Tyler Goble USMC

Project Summary

This research, working in conjunction with ongoing NPS efforts examining Expeditionary Advance Base Operations (EABO), focuses on exploring, assessing and identify mechanisms that will allow United States Marine Forces Special Operations Command (MARSOC) to better serve as a bridge for capabilities integration with SOF and deployed MAGTFs to fully maximize the complementary capabilities of each formation. Specifically, this effort examines MARSOC operating concepts with a focus on Strategic Shaping and Reconnaissance (SSR) and the tie-ins to the USMC Expeditionary Advanced Based Operations (EABO) concept for 21st Century warfighting in the contact, blunt, and surge layers of competition and conflict. This research examines SSR activities across the spectrum of cooperation, competition, and conflict to gain awareness of adversarial intentions and capabilities in order to deter, disrupt, deny or increase the adversary's risk.

The research leveraged the Naval Postgraduate School (NPS) Warfare Innovation Continuum (WIC) and multiple Joint Campaign Analysis (JCA) and Wargaming Applications courses to develop its insights.

The primary focus of this effort was to explore how MARSOC can operationalize SSR to achieve effects in competition in a littoral environment. The effort was based on an exchange of ideas between MARSOC and NPS researchers to better understand SSR operational concepts and identified three critical MARSOC issues for exploration. The research identified a potential set of SSR supported platforms and multiple operational techniques for the employment of those platforms.

Keywords: *wargaming, campaign analysis, expeditionary advanced based operations, EABO, marine air ground task force, MAGTF, marine forces special operations command, MARSOC, strategic shaping and reconnaissance, SSR*

Background

The Strategic Shaping and Reconnaissance (SSR) concept is the Marine Corps' special operations contribution to the national defense requirements for both strategic competition and, when required, conflict. SSR is an evolving MARSOC operating concept that ties into future special operations force (SOF) operations and the USMC Expeditionary Advanced Based Operations (EABO) concept for 21st Century warfighting in the contact, blunt, and surge layers of competition and conflict. SSR includes those activities conducted by special operations elements in cooperation, competition, and conflict to gain awareness of adversarial intentions and capabilities in order to deter, disrupt, deny or increase the adversary's risk. SSR encompasses a wide array of skills and equipment to provide shaping and influence effects. Effects are achieved through a hybrid approach utilizing selected SOF core activities and programs applied through special and intelligence operations, direct and indirect actions, and the persistent development of ally and partner relations.

Marine Special Operations Forces (MARSOF) conducting SSR possess the capability to operate in the competition continuum and transition to conflict if competition fails. MARSOF employs capabilities in the multi-domain environment that provide target analysis against networks in competition and conflict. Emphasis is placed upon strategic mobile targets, and critical infrastructure to determine intent, providing the supported commander current and detailed collections and, when required, Direct Action against a specific network, facility, or individual associated with threats against the nation's interests.

The wargames utilized in this work familiarized participants and observers with SSR concepts and their potential employment in a South China Sea scenario. Under the NPS WIC construct, an NPS student team, in the JCA course, conducted a mini-study examining a set of potential critical issues in an operational environment. This mini-study was followed by an NPS faculty-advised student wargaming team in the Wargaming Applications course, that designed, developed, conducted, and analyzed a wargame leveraging the findings from the mini-study. The wargames modeled SOF utilization of the principles of SSR in a competition environment to best posture SOF to deter escalation of events.

The overarching objective of this effort was to explore how can MARSOC operationalize SSR to achieve effects across the continuum of cooperation, competition, and conflict in a littoral environment. This effort focused on gaining insights into the following three major issues:

1. What maritime platforms best support an SSR mission in a littoral environment?
2. What tactics, techniques, and procedures (TTPs) should be used for littoral mobility in support of SSR missions?
3. How do external agencies, including the interagency, China, local media, and the special operations task force (SOTF) react to the SSR platforms and TTPs?

Findings and Conclusions
This effort resulted in the following findings and conclusions.

Issue 1: This effort examined the potential for SSR missions both in an island-hopping and riverine scenario. For island-hopping and intra-island missions, planning teams tended to select a variant of a medium size vessel that can carry 10-15 personnel, multiple parasite boats to go to and from shore, and possess a reasonable cargo capacity for either transport or mission equipment. A medium-size, host nation owned patrol boat, or a locally sourced fishing trawler appeared to be the best performing platform. For riverine missions, planning teams focused on either military or civilian-styled zodiac-class boats. Planning teams favored these platforms specifically for their ability to navigate shallow waters under motor power or while rowed.

Issue 2: The overwhelming majority of teams utilized overt actions to create a clear narrative for their actions. Many teams conducted bilateral, partner force training in conjunction with their mission to support a positive narrative. Additionally, teams often conducted recreational or commercial fishing and diving operations to add additional narrative.

Most planning teams incorporated the host/parasite platform technique in their operations. Utilizing a larger vessel as the host and tactical operations center allowed teams to disperse their forces in smaller vessels for their team insert and maintain a smaller footprint. The parasite technique allowed access to shallower waters without sacrificing the benefits of a larger vessel.

Teams often utilized larger than expected force sizes in conducting their missions. Fifty percent of the mission sets allowed the planning teams to dictate the number of troops, and fifty percent provided a troop constraint (i.e., you must insert 10 personnel). A minimum force size was dictated as 4 personnel. When planning teams were able to dictate the number of troops, the average team size was 12 personnel.

Issue 3: The SOTF viewed most missions that had a plausible innocent circumstance (i.e., partner training or recreational activity that fit into the scenario) as low risk. The SOTF was particularly concerned about the location of U.S. personnel and equipment, specifically when using a civilian-style boat.

China. As expected, China's reaction to US actions with a partner nation force were overall negative. It should be expected that China will disapprove of US rapport building operations, especially with training operations being conducted to increase the operational effectiveness of the partner nation forces (PNF).

Media. The local media tended to favor any US relation building or training assistance actions that provided a positive and growing relationship with a PNF. As an example, assisting in training PNF on visit, board, search, and seizure techniques and other waterborne interdiction approaches to help fight illegal fishing was regarded very favorably in the eyes of the media.

Interagency. Building relationships with interagency partners is critical to operations. Overall, interagency organizations were concerned about the potential impact operations involving civilian craft and using “innocent” recreational activities might have on the goodwill narrative of US involvement. This concern highlights the importance of command teams building good rapport with embassy country teams.

Recommendations for Further Research

Strategic Shaping and Reconnaissance (SSR) is still a nascent concept that require further research to better understand how the Marine Special Operations Forces MARSOF community can use it to operate more effectively to establish a position of advantage, while preventing the escalation of violence. Essentially, these employment mechanisms will need to mature through continued programs of wargaming and campaign analysis research to best serve the joint intermediate force capabilities office and the Special Operations Forces (SOF) community.

References

None

Marine Corps Systems Command (MARCORSYSCOM)

NPS-22-M254-A: Developing a Model-Based Systems Engineering (MBSE) Land Domain Construct for Marine Corps Systems Command

Researcher(s): Warren Vaneman, Corina White, and Ronald Carlson

Student Participation: Raymond Stone CIV

Project Summary

The purpose of this research was to develop and evaluate a generic ontology and conceptual data model (CDM) that was created to support the naval domain, for applicability to Marine Corps Systems Command (MCSC) and the land domain using Force Design 2030 (Congressional Research Service Insight, 2022) for overarching guidance. The generic ontology and CDM were developed as part of an exploratory study, which considered system data entities, attributes, and relationships. This research effort identified a generic ontology and defined a CDM that represents the system of interest from multiple perspectives and allows for the exploration of the system holistically. This is fundamental to the implementation of a model-based systems engineering (MBSE) environment. A parsimonious ontology allows system entities to be reduced to their atomic level, and then by establishing a CDM (i.e., data schemas) allows for a virtual representation of the system to be defined. The ontology and CDM identify areas where interfaces must be developed to exchange data and identify data boundaries between organizations, modeling languages, presentation frameworks, and tools. The study approach considers the importance of designing a generic ontology that comprehensively represents the system across the lifecycle, analyzes the relationships between entities defined within the ontology, considers the ontology as a foundation for an authoritative source of truth and finally, designs a modeling plan that depicts the recommended path to transition from document-based systems engineering to a true MBSE-based land domain. In summary, an ontology and CDM were developed to define the entities and relationships for an entire system throughout its lifecycle. These products were verified utilizing a mission thread from Force Design 2030 representing the USMC land domain. Utilizing this ontology and CDM, and the derived modeling plan, the MCSC can begin transitioning from document-based systems engineering to a true MBSE-based land domain.

Keywords: *digital engineering, model-based systems engineering, marine corps force design 2030, land domain, ontology, conceptual data model*

Background

MCSC strives to evolve from a traditional document-based systems engineering environment to an MBSE environment. The importance of MCSC transitioning to MBSE has recently been elevated when the Department of the Navy (DoN) assigned MCSC to define an MBSE environment for the land domain.

This represents a significant change for the Marine Corps since it marks the transition to mission-focused system design and development. This focus requires several Marine Corps Commands to coordinate their modeling efforts to insure a system-of-systems perspective with an end-to-end mission focus. The land domain is part of a larger DoN effort to model the full-spectrum of activities and systems within naval warfare. This effort is being prescribed to gain better insights, and make better programmatic decisions, to support system development and influence integration across the naval warfare domains. The purpose of this study is to develop an ontology, CDM, and a transition approach that can be utilized by the MCSC to transition to an MBSE-based environment for the land domain.

This research adopts a portion of the lifecycle modeling language (LML) ontology as the basis because it represents an ontology that uses an economy of entities that have defined relationships and attributes to create a parsimonious list of entities. This research is not promoting the use of the LML nor endorsing any MBSE tool based on LML. The LML entities are only used because they are well-defined, establish relationships, and are parsimonious. This type of ontology is known as an entity, relationship, attribute, or ERA. This research expanded the ERA ontology approach to include labels (ERA(L)). The labels allow for data to be further identified within an entity class to entity subclasses. Finally, to further facilitate mapping a data type was added.

Once a comprehensive ontology was created, the relationships between the entities defined within it were examined. This formal structure resulted in a CDM that serves as the basis of a common terminology and structure. This generic ontology and CDM were validated using real world systems. Three interim test cases were utilized, the Amphibious Combat Vehicle, Joint Air Domain Command and Control (JADC2) concept as well as the Marine Corps Enterprise Network (MCEN) architecture. Lastly, a mission thread derived from the United States Marine Corps (USMC) reorganization taking place under the Force Design 2030 initiative was utilized. Since the goal is to examine the entire lifecycle of a system, the conceptual data model is all inclusive but for presentation has been segmented into sections. A fundamental premise of this research is that an ontology should use an economy of entities approach to create a parsimonious list that allows entities from a data dictionary to be reduced to their atomic level, thereby identifying like entities. A parsimonious ontology is important to focus the engineers on a limited (but comprehensive from a systems perspective) set of entities. Having too many entities may lead engineers to use different entities for the same system element. Conversely, having too few entities will not fully identify the system elements.

Findings and Conclusions

The ontology was developed to reduce seemingly disparate entities from various program data dictionaries to the "atomic level" using a parsimonious set of entities. The relationships between them were then established in the CDM. In an ideal system model, each data type will be represented only one time as it is in the real-world, but can be viewed from several perspectives.

For MBSE to be successful, the full scope of the system should be modeled, most likely via different MBSE tools that represent a portion of the system. The purpose of the CDM is to model the various aspects of the system, using the ontology entities and relationships to create a virtual representation of the system. Using a combination of the ontology and CDM facilitates a "Rosetta Stone" to exchange data between different modeling languages, MBSE tools, and presentation frameworks, thus allowing system data to be developed with the best approach for the problem.

The Land Domain, as articulated in Force Design 2030, was applied to both the ontology and the CDM. Utilizing the developed ontology and the CDM, the system entities related up to the highest-level missions defined by strategic guidance as well as were decomposable and defined by the lowest levels of components. In the USMC, the series of model creation and ownership resides at various levels starting with Combat Development and Integration (CDNI), USMC Systems Command (SYSCOM), program offices, contractors as well as the multitude of subcontractors and other government components. Utilizing a defined ontology and CDM ensures that as different organizations create the various levels of the model, utilizing various languages and MBSE tools, the final product will have a consistent schema and fully represent the system.

In summary, an ontology and CDM were developed to define the entities for an entire system throughout its lifecycle. These products were verified utilizing a mission thread from Force Design 2030 representing the USMC land domain. The USMC Systems Command can now utilize the developed ontology and CDM, along with the derived modeling plan, to begin its path towards transitioning from document-based systems engineering to a true MBSE-based land domain. Continued research will also be accomplished to verify this ontology and CDM against a wider set of systems and domains both within the Naval Domain as well as other services.

Recommendations for Further Research

This research has made great advances in defining a universal ontology and conceptual data model (CDM). The following opportunities for further research were identified.

First, while this research applied the generic ontology and CDM to the United States Marine Corps land domain, additional effort is needed to demonstrate its applicability to other domains. Validating the ontology and CDM with the Naval Operational Architecture, as well as other service component models such as the Army, is recommended. The success of this proposed research will enable the standardization of an ontology and CDM.

Second, for the ontology and CDM to be most effective, it needs to be implemented as a formal data exchange standard. An exploration of approaches that represent the complex knowledge about entities, the relationships between entities, and additional information needed to exchange data will provide a more holistic and comprehensive view to share data across various modeling languages, model-based systems engineering tools, and presentation frameworks.

Third, additional "model curation" research is needed. Currently, few efforts are exploring how system models will be governed in the future. Implementation of a universal ontology and CDM will require a more defined process for "model curation."

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N1 - Manpower, Personnel, Training & Education

NPS-22-N098-A: OFRP Phase Variation in Signature and Destructive Behaviors

Researcher(s): Kathryn Aten, Panagiotis Matsangas, Anita Salem, Simona Tick, Nita Shattuck, and Valentina Palazzetti

Student Participation: No students participated in this research project.

Project Summary
This project resulted in the design of a study for future research to investigate the destructive behavior surge during the maintenance phase of the Optimized Fleet Response Plan (OFRP). The Culture of Excellence Campaign's Perform to Plan effort will empower warfighting capability by fostering psychological, physical, and emotional toughness. To meet this goal, the Navy needs to understand what encourages signature behaviors and reduces destructive behaviors and how these behaviors impact readiness. This research resulted in a detailed questionnaire based on validated instruments that align with the behaviors the Navy has identified as signature and destructive behaviors, interview questions and research recommendations as well as materials to submit to IRB and OMB for approval for data collection. The study design was developed to guide data collection, which will provide critical insight to encourage signature behaviors and counter destructive behaviors.

This study found that Navy signature and destructive behaviors align with extent research such that validated instruments can be used in future Navy studies. Researchers designed a study for future research. The design for future research involves a mixed-methods, explanatory sequential study to answer three research questions: a) What are the rates of signature and destructive behaviors during phases of OFRP? b) Do rates differ by command type? c) How do signature and destructive behaviors impact readiness? We recommend using the developed instruments to survey and interview sailors on ships across the OFRP phases.

Keywords: *optimized fleet response plan, OFRP, signature behaviors, questionnaire*

Background
Healthy work cultures are safer and more productive. Workplace stress costs the U.S. economy more than $500 billion, results in the loss of 550 million workdays each year due to stress on the job, and is the cause

of 60% to 80% of workplace accidents (American Psychological Association, 2015 in Seppala & Cameron, 2015). Reducing stress is likely to have significant effects on individual and organizational well-being and performance. Research has shown that improvement in organizational positivity in organizations predicts indicators of effectiveness (Cameron et al., 2011).

Congruent with research findings, the chief of naval operations has directed the Navy to create a Culture of Excellence, noting that by focusing on positive, signature behaviors, the Navy can build and sustain a lethal force of tough sailors who are ethical and masters of their trade. The Navy has identified 10 signature behaviors to drive a culture of excellence: treat every person with respect, take responsibility, hold others accountable, intervene when necessary, be a leader and encourage leadership, embrace diversity, uphold integrity, exercise discipline, and contribute to team success.

The Culture of Excellence Campaign's Perform to Plan effort will empower warfighting capability by fostering psychological, physical, and emotional toughness. To meet this goal, the Navy needs to understand what encourages signature behaviors and reduces destructive behaviors and how these behaviors impact readiness.

The study mapped existing literature to Navy identified signature and destructive behaviors to identify validated instruments that could be used to answer the following questions: a) What are the rates of signature and destructive behaviors during phases of OFRP? b) Do rates differ by command type? c) How do signature and destructive behaviors impact readiness? First, researchers conducted an extensive literature review and mapped constructs and measures in the literature to Navy identified signature and destructive behaviors. Then, the researchers identified validated instruments that can be used to assess Navy signature and destructive behaviors.

Findings and Conclusions

This study found that Navy signature and destructive behaviors align with extent research such that validated instruments can be used in future Navy studies. The output of this study was a design for future research. The resulting study design will utilize a mixed-methods, explanatory sequential approach to include two major components. The first component would involve collecting data from Sailors on surface ships of the United States Navy. The second component would involve conducting semi-structured interviews with Sailors on ships to elaborate on the quantitative findings of the first component of the study.

Collecting this type of data will require a lengthy approval process through the Office of Management and Budget. This will require 12 to 18 months, which is outside of the duration of a single NRP funding cycle.

The researchers developed a questionnaire by mapping Navy signature and destructive behaviors to validated instruments in the literature. The questionnaire we developed includes items grouped into five sections: demographic and occupational characteristics, health and health/performance-related behaviors, active-duty service member state, destructive behaviors, and signature behaviors. The interview questions are semi-structured, designed to solicit rich accounts and perceptions.

Given the importance of signature and destructive behaviors in Sailor state, we propose a phased, multi-year, project to study this topic. The first phase of the study should focus on a small number of ships to include both questionnaires and focus groups. Even though the findings of this first phase will be limited in terms of their generalizability, the use of researchers to interact face-to-face with Sailors (during the recruitment and data collection) will lead to better quality data, fewer missing data, and higher compliance with the study protocol compared to methods in which the researchers do not interact with the Sailors. The second phase of this project will be focused on collecting destructive behaviors data from all surface ships using an online survey method. From a theoretical standpoint, the data collected with this online approach will be more representative of the Sailor population. However, earlier research in the military using online questionnaires suffered from a low response rate. For example, a recent online survey in three USMC units had an average response rate of 7.5% (Matsangas et al., 2021), whereas the response rate of a large-scale survey study conducted in 2018 in the USMC and the USN was 6.6% and 6.7%, respectively (Meadows et al., 2018).

Recommendations for Further Research

Future research should investigate behavior shifts during the Optimized Fleet Response Plan phases using the instruments developed through a broader study and stratified sample of Sailors.

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NPS-22-N099-A: Behavioral Techniques for Improved Performance and Recovery during Sustained Stressful Periods

Researcher(s): Simona Tick, Nita Shattuck, Panagiotis Matsangas, and Kathryn Aten

Student Participation: Stephen Gagnon

Project Summary
This study conducts a meta-narrative analysis of prior studies to identify effective stress management and recovery techniques compatible with Navy environments. The study aligns the Navy's Culture and Resilience goals to empower Sailors to tolerate and recover from stress; to foster toughness, trust, and connectedness throughout the Fleet; and to build a more lethal warfighting force. This study is the first of a phased two-study effort, with the second study to be proposed in a subsequent program cycle. For the initial study, the research team conducts a broad-scope literature review from a whole-person primary prevention perspective to identify effective stress-optimization and recovery techniques and to map them with the Navy-specific components of the Total Force Fitness (TFF).

Further, the study develops and administers a questionnaire to augment the meta-narrative analysis and capture the prevalence of behavioral techniques Sailors use to manage stress, the frequency of use, and Sailors' attitudes towards using them. In addition, the researchers catalogue Navy stress management programs and resources aimed to support stress prevention and stress recovery for Sailors. These three approaches help inform assessment plans for stress prevention and recovery effectiveness within the Navy Culture and Force Resilience programs.

Keywords: *behavioral techniques, stress recovery, readiness, sailor 2025, culture of excellence, culture and resilience*

Background
Stress affects the physical and the mental health of individuals and impacts their performance. Research has shown that the effectiveness of behavioral techniques for coping and support varies across different populations (Deuster & O'Connor, 2015; Antony et al., 2020). While stress-optimization and recovery techniques have been investigated, these techniques have not been assessed in healthy people nor from a holistic whole-person, primary prevention perspective. It is unclear what behavioral techniques would be most effective for decreasing acute stress response in the Navy work environment.

Sailors must have the skills to adapt to the extraordinary challenges that are part of Navy life. The DOD's Integrated Primary Prevention Policy directs military departments to promote total force fitness and resilience, which are essential to peak performance. To meet this goal, there is a need to better understand what stress-optimization and recovery techniques, or combination of techniques can be most effective for decreasing acute stress response in Sailors.

This study identifies effective stress management and recovery techniques compatible with Navy environments. It then maps them to the Navy-specific components of TFF to develop a typology of techniques and components. This study aims to inform plans to assess effectiveness of programs within the Culture and Resilience and Integrated Primary Prevention efforts to promote total force fitness and resilience of warfighters and to reduce unplanned losses.

The study addresses the following research questions:

1. What stress-optimization and recovery techniques, given prior published studies, may be effective in building stress tolerance and managing acute stress response of Sailors?
2. What combinations of stress-optimization and recovery techniques, given prior published studies, may be effective in building stress tolerance and managing acute stress response of Sailors?
3. How do these behavioral techniques compare to the techniques Sailors are currently using?

Findings and Conclusions

The study uses an inductive, iterative approach for selected articles for a thematic analysis needed to ensure rigor and alignment given that the literature is not organized in line with the components of the Sailors' total fitness. The approach is supplemented with a software-aided, bibliometric semantic analysis. The two approaches identify themes that are hypotheses of what could be effective, to be assessed in the phase two study. The studies selected for analysis are published from 2012 to 2022 in top-rated journals in five disciplines: organizational management, sports medicine, medical physiology, psychology, and psychiatry. Initial iterative selection generated a sample of 1,187 articles from 11 journals. For the thematic analysis, we further selected a representative sample of 38 journal articles.

From the literature review, we find that (a) effective stress recovery techniques align most strongly with the psychological, social, and spiritual components of the total force fitness perspective; (b) they include, most frequently, approaches centered around mindfulness; and (c) they are typically facilitated by clinical professionals.

To augment the literature review and to assess the prevalence of behavioral techniques Sailors use to manage stress, the frequency of use, and Sailors' attitudes towards using them, the research team develops a questionnaire and administers it to a purposeful and theoretical participant selection at a sea command and at a shore command.

In addition, the researchers catalogue Navy stress management programs and resources aimed to support stress prevention and stress recovery for Sailors.

From the data collected we find that Sailors use a large array of measures to build their tolerance to stress, with most used behavioral techniques centered around mindfulness. We find, however, that awareness of existing Navy stress reduction programs and resources is low, especially among junior Sailors.

In summary, the phase one study of the planned two studies identifies effective behavioral techniques from prior investigations, as hypotheses to be assessed, then mapped them to the components of the TFF and compared them with a data sample on prevalence of behavioral techniques used by Sailors and their awareness of available Navy programs and resources to support them in prevention and recovery from stress.

The findings overall help facilitate planning and implementation of assessment and refinement of curriculum to navigate stress and of training for deck-plate leaders aimed to enhance their ability to provide whole-Sailor primary prevention and improve resilience.

Recommendations for Further Research

To support efforts of the Navy to foster toughness and to build a more lethal warfighting force, Sailors must be empowered to use skills and techniques to manage stress and adapt to the extraordinary challenges that are part of Navy life. This study identifies effective stress-optimization and recovery techniques from prior investigations that are suitable for Navy contexts, maps them to the components of the total force fitness, and compares them with data from a targeted sample on prevalence of behavioral techniques used by Sailors. Future studies can use findings from this study to assess the recommendations within the Culture and Force Resilience programs and provide the optimum dosage and frequency of stress optimization and recovery techniques. Further, future studies can generate refinements of curriculum to navigate stress and improvements in training for deck-plate leaders aimed to enhance their ability to provide whole-Sailor primary prevention and improve resilience.

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NPS-22-N100-A: Assessment of Navy Performance Evaluation

Researcher(s): Latika Hartmann, and Sae Young Ahn

Student Participation: LT Matthew Faber USN

Project Summary

This study takes a three-pronged approach to assessing the Navy performance evaluation system using an across-service comparison, focus groups of Navy subject matter experts, and a survey of a representative group of Navy enlisted sailors and officers. Our across-service comparison finds the Navy is unique in offering fewer narrative blocks to raters, not formally using multiple raters, and using an average of the individual evaluation traits as a summary measure of both comparative assessment and potential. The focus group respondents recommend a rating/community specific evaluation, replacing the current forced distribution ranking with reporting seniors writing a letter to the promotion board, more centralized training on writing honest evaluations and a fully electronic system for submitting evaluations. Finally, survey respondents also recommend better training of reporting seniors like the focus group respondents. They also recommend changing the evaluation timing such that reporting seniors evaluate sailors/officers under them that have served for the same length of time.

Based on our assessment, we recommend the Navy (1) consider separating the individual evaluation of traits from the comparative assessment and potential piece of the evaluation, (2) offer better training led by experienced reporting seniors on writing clear, honest, and informative evaluations, (3) change the timing of evaluations such that summary groups do not include individuals that have served for widely different lengths of time under the same reporting senior, (4) formally incorporate more reviewers or raters in the evaluation process, and (5) reduce the administrative burden of the evaluation process.

Keywords: *navy performance evaluation, officer fitness reports, enlisted evaluations*

Background

Identifying and promoting talent is key to increasing efficiency and productivity in any organization. This is particularly important for the Navy and U.S. military because individuals are promoted from within the system, and there is less scope to hire individuals into higher level positions. To that end, Navy talent management has received considerable attention in recent years with growing calls for modernizing the evaluation system, which went through its last major overhaul in the 1990s. As the Navy moves forward with the Navy Performance Evaluation Transformation and a new Performance Evaluation System, this project is a valuable and timely assessment of the present system.

This study uses a three-pronged approach to assess the Navy Evaluation system. First, we compare the Navy evaluation instruments, namely Fitness Reports (FITREPs) and evaluations (EVALs) to forms used by the other services. This exercise identifies common across-service themes in the evaluation instruments and highlights areas where the Navy differs from the other services. Second, we solicit feedback from Navy subject matter experts (SMEs) and stakeholders in small focus groups on (1) the current system, namely what works and what does not work, and (2) their top recommendations to reform problems with the current system. Third, we use feedback from the focus groups as inputs in a survey to solicit feedback on proposed reforms from a larger and more representative group of Navy enlisted sailor and officer respondents. This research supports current Performance Evaluation Transformation efforts being led by Navy Personnel Command and Task Force One Navy #2 on Talent Management.

Findings and Conclusions

Our across-service comparison finds that the Navy FITREPs/EVALs share common features with the other services in documenting background information on the ratee, their rater(s), and some traits. Yet, the Navy is unique in offering fewer narrative blocks to raters, not formally using multiple raters, and using an average of the individual evaluation traits as a summary measure of both comparative assessment and potential, which diminishes the quality of the feedback received by a sailor/officer.

In the focus groups, Navy SMEs recommended solutions in four major areas. First, respondents recommend a rating/community specific evaluation with each rating/community defining their "best and fully qualified." Second, respondents recommend replacing the forced distribution ranking of promote (P), must promote (MP), and early promote (EP) with reporting seniors writing a letter to the board with their promotion recommendation. Third, respondents recommend more training of reporting seniors to guard against inflated evaluations and instill more honesty and accuracy in the evaluation. Finally, respondents recommend a fully electronic system with more space for the narrative block.

Drawing on a larger and more representative group of Navy personnel, our survey finds no dominant popular or unpopular reforms in the dimensions to increase either "feedback to sailors" or "honest and accurate assessments." Under the domain of "clarity for personnel decisions," the winning reform is changing the timing of evaluations such that sailors/officers are evaluated after having served a minimum length of time under a reporting senior. Under the same category of "clarity for personnel decisions," the least popular proposed reform is to reduce the number of competitive categories for officers to unrestricted line, restricted line, and staff corps. For increased "ease of use," most respondents dislike the idea of allowing promotion board members to review records before arriving at the selection boards. For increased "alignment with Navy expectations," respondents are nearly unanimous in rejecting the proposal to periodically change the evaluation forms to include priorities of the Chief of Naval Operations, while the most popular reform by far is to provide consistent and centralized training to reporting seniors in writing evaluations. Finally, while we find significant differences in the views expressed by enlisted and officer ranks, we find no significant differences in views about the system and the proposed reforms by gender or race.

Based on our assessment, we recommend the Navy (1) consider separating the individual evaluation of traits from the comparative assessment and potential piece of the evaluation, (2) offer better training led by experienced reporting seniors on writing clear, honest, and informative evaluations, (3) change the timing of evaluations such that summary groups do not include individuals that have served for widely different lengths of time under the same reporting senior, (4) formally incorporate more reviewers or raters in the evaluation process, and (5) reduce the administrative burden of the evaluation process.

Recommendations for Further Research

If our proposed recommendations to reform the current Navy Evaluation system are implemented, we recommend further research to ensure sailors/officers, reporting seniors, and promotion board members have a clear and unambiguous understanding of each piece of the reform and its implication for the evaluation process. If more training is required for reporting seniors to write effective evaluations, we recommend further research on the appropriate form of such training, namely the timing in the career pipeline of sailors/officers, training method (i.e., in person or online), and outcomes to assess the effectiveness of the training. The Navy should also investigate methods to identify experienced, fair, and accurate reporting seniors to serve as trainers. If the Navy changes the timing of evaluations as recommended such that summary groups do not include individuals that have served for widely different lengths of time under the same reporting senior, this will require significant administrative changes involving many steps that will affect both the evaluations and their interpretation by promotion boards. We recommend further research as this reform is implemented allowing the Navy to course correct if necessary. Finally, we recommend the Navy consider continuously evaluating the system as reforms are enacted, which would allow for changes and updates to correct issues as they are discovered, as opposed to major overhauls every 20 years or so.

References

None

NPS-22-N128-A: Reducing Stigma and Encouraging Help-Seeking Behavior

Researcher(s): Deborah Gibbons, Alan Nelson, and Susan Aros

Student Participation: No students participated in this research project.

Project Summary

This project asked how the United States Navy could communicate more effectively with Navy personnel who may require help for drug or alcohol misuse. Communication choices, including the way messages are framed, can affect stigma and individuals' willingness to seek help, so Navy documents, websites, and individual messages should be designed strategically. To support advancement in communication about drug and alcohol misuse, this research collected experts', enlisted personnel's, and officers' perceptions of Navy communication, potential message frames, and organizational factors related to help-seeking for drug and alcohol misuse. Specific perceptions included framing effects on stigma and Navy co-workers' willingness to seek help, as well as organizational obstacles and facilitators of help-seeking.

Results indicate that formal and informal communication affects perceptions of stigma and willingness to seek help. Participants in the study reported that fear-focused themes in formal Navy communication increase stigma and decrease help-seeking, while recovery-based themes have positive effects. Informal stories about help-seekers' experiences influence others' decisions about whether to seek help, and success stories can be particularly effective in reducing stigma and encouraging people to get help. Potential message frames received higher ratings when they presented objective information or focused on positive outcomes. Men responded more positively than women to messages about performance benefits, whereas women responded more positively to messages about personal growth, caretaking, and protecting their careers. Senior officers' perceptions differed significantly from those of enlisted personnel with regard to message frames and perceived organizational support for help-seeking. The report concludes with recommendations to encourage help-seeking by Navy personnel for issues with drugs or alcohol.

Keywords: *addiction, mental health, help seeking, stigma, drug misuse, drug abuse, alcohol misuse, message framing, Navy communication*

Background

The United States' Department of Defense's (2020) Integrated Primary Prevention Policy directs the military departments to foster an environment that reduces stigma and promotes help-seeking for drugs or alcohol. Communication choices, including the way messages are framed, can affect stigma and willingness to seek help. To support advancements in communication about drugs and alcohol, this research considered the effects of message framing alongside broader influences such as organizational culture and processes in the U.S. Navy. Topics under investigation included experts', enlisted personnel's, and officers' perceptions of Navy communication, potential message frames, and organizational factors related to help-seeking for drugs and alcohol misuse. Specific perceptions included framing effects on stigma and Navy co-workers' willingness to seek help, as well as obstacles and facilitators of help-seeking.

The team interviewed 10 subject matter experts, including seven Alcohol and Drug Control Officers, one Drug and Alcohol Program Advisor, a psychologist embedded with a special warfare group, and a private practice therapist. Thirty-one volunteers completed pre-surveys about message frames and organizational issues, then participated in focus group meetings. Enlisted personnel and officers met in separate focus groups, as did men and women, to discuss these issues. A subsequent survey addressed issues raised during interviews and focus group meetings, as well as phrases excerpted from a current Navy document that provides policy and procedures related to substance misuse. The survey was answered by 63 respondents, but only 32 of them completed a significant number of questions. Despite this small sample size, trends and statistically significant differences in perceptions between men and women, enlisted and officers, occurred.

Findings and Conclusions

The expert interviews provided insights into how stigma and stigmatizing language affect willingness to seek help. Language that emphasizes punishment or fear can reduce help-seeking by increasing Sailors' concerns about career derailment. Communication about confidential sources of help and potential benefits of getting help can encourage people to act. Experts further emphasized that people who seek help need clearer information about the necessary processes.

The pre-survey and focus groups indicated that people are deterred by stories about negative experiences others have had when they sought help, whereas success stories reduce stigma and encourage help-seeking. Focus group participants rated fearful themes lower than messaging about help and benefits to the individual, although a few male officers approved of the negative frames. Message themes that participants regarded positively included objective information about recognizing when someone needs help and how to seek help without negative career consequences. Follow-up survey respondents likewise preferred objective information and encouraging messages, as well as relatable examples of Navy personnel who have successfully sought treatment and gone on to accomplish their goals. Respondents further highlighted the need for the chain of command to support a healthy help-seeking culture.

Differences emerged between men and women, enlisted and officers. Officers favored family, career, and team-related message frames, while enlisted personnel emphasized more personal outcomes. Officers more commonly thought seeking help had been normalized in the Navy, whereas enlisted did not. Men responded more positively than women to messages about performance benefits, whereas women responded more positively to messages about personal growth, caretaking, and protecting their careers.

Survey respondents assessed specific passages from a Navy document about drugs and alcohol. Navy passages were rated as reducers of stigma and increasers of help-seeking when they provided information about recovery plans and ability to continue one's career. Navy statements emphasizing negative effects of substance misuse were seen to increase stigma and reduce help-seeking. Respondents identified several organizational factors that support or deter help-seeking in their work units. Concern about coworker attitudes, perceptions, and behaviors was seen as moderately deterring help-seeking. Inability to get an appointment was named as the strongest structural deterrent, and lack of time due to job demands was cited as a moderate deterrent.

Based on these findings, the following interventions are recommended:

1. Navy documents should consistently communicate about substance misuse as a treatable health problem, emphasizing potential benefits of help-seeking.
2. Share authentic, relatable, personal testimonies from people who got help.

3. Ensure that every Sailor knows how to find confidential help with minimal risk to career.
4. Design factual messages to reduce uncertainty about the process of obtaining help for drugs or alcohol.
5. Address systemic chokeholds that delay access to help.
6. Educate officers about enlisted personnel concerns and teach them necessary skills to establish a supportive culture for help-seeking.

These recommendations could reduce stigma and increase willingness of Navy personnel to seek help. Results of this study may inform changes to language for development of OPNAV Instruction 5350.4E and future communication about help for drug and alcohol misuse.

Recommendations for Further Research

Stigma related to substance misuse increases fear of peer ostracism, career derailment, and team exclusion. In the U.S. Navy, open discussions with designated, trained facilitators could move communities toward normalizing help-seeking. Further research is needed to identify crucial elements of such discussions, to develop discussion materials, and to create user-friendly guidance to prepare people to lead the discussions.

Education-based message framing needs to be contextualized to the dynamics of specific audiences. Despite efforts in this study to compare the interests and attitudes of discrete Navy communities, we were not able to obtain adequate participation. Future research is needed to develop strategic communication plans that could be tailored to members of distinct Navy communities.

Demographic differences impact perception and response to communication about drugs and alcohol. Officers responded more favorably to messages emphasizing family, career, and especially team. Enlisted members tended toward more individualistic themes. Women were more favorable to a variety of positive message frames than were men. The idea that 'not every Sailor is the same' came up several times in the discussions. Additional work is needed to fine-tune communication strategies to reach each of these distinct demographics.

A multi-faceted approach to reduce stigma and increase help-seeking would involve teaching leaders to communicate effectively about drug and alcohol misuse and to create a supportive organizational climate. Future work could develop appropriate educational materials for senior enlisted and officers, based on the current research about message framing and on best practices for training facilitators.

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NPS-22-N137-A: Performance Evaluation Trait Validation

Researcher(s): Erik Helzer, and Marigee Bacolod

Student Participation: LTJG Bryan Luke USN, and LT Phillip Gervato USN

Project Summary

We present the results of a year-long study supporting the Navy's efforts to transform its existing Performance Evaluation System (PES) with an evaluation tool that has been updated to reflect current Navy values and priorities. Our team validated and refined trait and value statements (TVS) developed for rating Sailors on a variety of dimensions, including leadership, teamwork, communication, resilience, and other character strengths. In addition, our team developed rating scales for assessing Sailors' future potential for performance at the next paygrade, as well as a comparative assessment tool for evaluating Sailors against their peers. We then conducted a large-scale prototyping study, which involved the development of a performance evaluation prototype instrument, recruitment of Sailors-reported-on and performance raters, and statistical analysis of the properties of the prototype instrument—in particular, the measurement validity of the TVS. Using data from 606 performance raters, we find that ratings of Sailors based on past performance and future potential predict comparative assessments, with some traits (e.g., leadership) better distinguishing the top from middle performers. Few of the trait ratings distinguished among bottom performers, although such performers were relatively rare in our sample. Ratings based on past performance and future potential were correlated with one another; analyses indicate they convey unique information about the Sailor-reported-on, but that both predicted workplace behaviors. Based on our research, we offer four concrete recommendations for action. First, we recommend amplifying the comparative assessment in future PES. Second, the Navy should consider adopting ratings of future potential for developmental/coaching purposes using actionable, concrete developmental feedback. Third, future evaluation instruments should focus on a subset of performance and/or future potential traits in assessing job performance to keep PES simple and useful. Finally, we recommend assessing the predictive validity of these new measures using multi-source data.

Keywords: *performance evaluation system, performance assessment, traits, job performance, measurement validity, reporting senior's cumulative average, RSCA*

Background

A valid and credible PES is critical for identifying and managing talent in the U.S. Navy. The Navy's Sailor 2025 initiative called for an updating of the Navy's personnel management system to reflect the Navy's current goals with respect to recruitment, retention, and advancement (Burke, 2018). In addition, concerns expressed by Task Force One Navy point to the need for a PES that is both fair and objective (Task Force One Navy, 2021). Major efforts to generate updated performance trait statements that are consistent with Navy doctrine, instructions on performance appraisal, and Sailor values were conducted in 2002 (under the Task Force Excel 5-Vector Model) and 2019 (by researchers associated with the performance evaluation transformation initiative). In 2019, a working group identified TVS to serve as the basis of revised performance evaluation metrics. This set of TVS modernizes the performance criteria against which Sailors would potentially be evaluated; however, a systematic study on the validity of this set of TVS has not been conducted.

We executed a year-long study supporting the Navy's efforts to transform the existing PES with an evaluation tool that has been updated to reflect current Navy values and priorities. We validated and refined the TVS, benchmarking items against current Navy doctrine and performance evaluation materials from other military services. We then conducted a large-scale prototyping study, which involved the development of a performance evaluation prototype instrument, recruitment of Sailors-reported-on and performance raters, and statistical analysis of the properties of the prototype instrument—in particular, the measurement validity of the TVS.

We recruited Sailors-reported-on through two different channels, including a large-scale social media advertisement. These Sailors (N = 1823) furnished the names and contact information of performance raters (e.g., supervisors, peers) who could meaningfully evaluate Sailors' job performance. Performance raters were directed to an online platform allowing them to evaluate Sailors using the performance evaluation prototype. Usable responses were collected from 606 performance raters and were statistically analyzed to assess the validity of items comprising the performance evaluation prototype.

Findings and Conclusions

Ratings of traits related to past performance and future potential were all correlated with measures of positive and negative workplace behaviors in the expected directions. Those rated highly on performance and potential tended to engage in organizational citizenship behaviors more frequently and counterproductive workplace behaviors less frequently than their peers.

We assessed whether the trait ratings had predictive validity using survey responses on the comparative assessment as the criterion. All the past performance traits had some predictive power, and some traits were better at distinguishing the top from the middle of the performance distribution. For example, ratings of leadership and initiative based on past performance were better able to distinguish the top from the middle performers, but ratings of character and resilience based on past performance were better at distinguishing the bottom from the middle performers. On the other hand, the future potential trait of experience and competence was able to distinguish both top and bottom performance.

A. Recommendation 1: *Amplify the comparative assessment in future PES.*

To differentiate talent and provide useful information to promotion boards and talent managers, we recommend amplifying the comparative assessment in future PES. Of all the job performance indicators assessed in our prototype, none was as informative in differentiating performance as the comparative assessment.

B. Recommendation 2: *Consider adopting future potential ratings for developmental/coaching purposes, especially the word blocks for actionable, concrete developmental feedback.*

Trait items based on future potential provide a unique source of information that may be ideal for the purpose of development and coaching. In this study, Sailors were evaluated on six trait dimensions (e.g., *character development*, *leadership and teamwork skills*, *judgment and decision-making*) based on their readiness to succeed at the next paygrade or in key, particularly demanding jobs. The benefit of this rating system is that it is forward-focused and constructive. When Sailors were rated as "not ready," we prompted respondents to offer concrete, actionable feedback to help the Sailor move toward greater perceived readiness. These trait ratings and qualitative feedback could serve as the basis for coaching sessions with Sailors to identify focus areas for job performance improvements that can advance them toward their next career milestone.

C. Recommendation 3: *Focus on a subset of performance and/or potential traits in assessing job performance to keep PES simple and useful.*

To reach the goal of transforming the PES toward a model that is simple, useful, and fair, we recommend focusing on a subset of the traits rating past performance and/or those rating future potential. Ratings of past performance are potentially simpler and more useful indicators of job performance than ratings of future potential.

Recommendations for Further Research

Our current efforts are focused on merging data from Sailors' personnel records with data from our prototype testing to expand our view of predictive, convergent, and divergent validity of the trait and value statements (TVS). These data and resulting analyses are critical to understanding how well ratings of Sailors' job performance using the refined set of TVS reflect and track with job performance on a longer time horizon across multiple indicators of performance. These data will also allow us to carefully examine potential adverse impacts of the refined TVS, including the question of whether some TVS inappropriately favor certain groups over others. We caution against implementing the TVS into performance evaluation tools until the results of these analyses are obtained.

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NPS-22-N277-A: Preparing Engineering Duty Officers (EDOs) for Command of Major Acquisition Shore Commands and Major Acquisition Programs

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Student Participation: Mark Brown USN

Project Summary

The U.S. Navy's capabilities regarding the design, acquisition and maintenance of ships and shipboard systems needs continuous improvement to counter advancing threats. Engineering duty officers (EDOs) have long been associated with these capabilities in both technical and leadership positions. Over the years, the range and complexity of these professional areas have increased, requiring the need to better understand the developmental leadership opportunities needed to increase the probability of success at command of major acquisition shore installations and programs. This study centers on analysis of the fundamental leadership requirements for EDOs. Using an inductive qualitative research approach, we examine the EDO career path and the main contributors to EDOs' preparation for command, when compared with other naval officer communities. Given that the EDO community is associated with a wide variety of jobs, we focus on commanding officers for regional maintenance centers (RMCs) and supervisors of ship building (SUPSHIPs).

Based on our findings from in-depth interviews with current and former commanding officers for RMCs and SUPSHIPs, we find that while technical expertise is a necessary foundation, leadership is central to successful command. Further, we find that while education, training, experience, and mentoring are important for successful command, personality also matters. The EDO commanding officers (COs) provide not only technical, but also contractual and business oversight for Navy shipbuilding and maintenance contracts accomplished in the private sector. The education and training of EDOs is found to be lacking in business and management understanding. Officer in charge experience at RMC detachments or prior RMC experience before RMC command can be beneficial, as well as management or business graduate degrees. The talented EDO officers are driven by the critical mission to support the U.S. Navy's shipbuilding and maintenance capabilities. The recommendations in this study aim to further increase the chance of successful RMC command.

Keywords: *engineering duty officers, EDO, leadership, best practices, talent management, career development, regional maintenance centers*

Background

This study focuses on the analysis of fundamental leadership requirements for EDOs to increase the chance of successful oversight of large, complex civilian organizations such as for RMCs and SUPSHIPs.

The EDOs use technical and leadership skills to lead shore acquisition commands that provide on-site technical, contractual, and business oversight for Navy new construction shipbuilding, repair, and modernization contracts accomplished in the private sector. The demands and complexity of these positions have increased over time, requiring a need to evaluate the development opportunities for EDOs in comparison with other naval officer communities.

The objective of the study is to take a focused look across the engineering duty community on the EDO career path and how it prepares EDOs to lead major shore acquisition commands such as regional maintenance centers. This study addresses the following research questions: (1) What leadership education, training and career development experiences contributed to successful EDO command tours, compared to those of other naval communities? (2) What career development and leadership preparedness best practices from other Navy communities can support successfully completing command tours for the EDO community? (3) How do the talent management practices of the EDO community compare to other officer communities and industry? Where can the EDO community improve?

To address these questions, this study uses well-established inductive theory building methods to help us develop our understanding from the data themselves rather than relying on a deductive, top-down approach. The inductive approach allows us to focus in more detail on understanding the main challenges faced by EDOs' COs, identifying key contributors to their successful command, and finding what can the community do differently to support the career development and chance of success for demanding jobs such as COs for RMCs and SUPSHIPs. We employ three sequential and iterative techniques for data collection: document review, strategic contact, and interviews. This approach provides a systematic process for qualitative research that guides and encourages repeated iteration of data collection and analysis (Eisenhardt, 1989). Such repeated iteration, noted widely as key to grounding theory in the data of a qualitative study (Glaser & Strauss, 1967), enables us to focus persistently on the EDO community as a potentially unique and revelatory case to study (Yin, 1994). The semi-structured interviews (Rubin & Rubin, 1995) comprise the central method for collecting our qualitative data. Our sample focuses on former and current commanders viewed as successful by the Navy, whether they are EDOs or from other naval communities. The interviews are conducted with O6s and above who are commanding or have commanded either RMC or SUPSHIP organizations. The interviews are conducted with probing (Nelson et al., 2000) and snowballing (Reich & Kaarst-Brown, 1999) techniques, and they continue until theoretical saturation (Glaser & Strauss, 1967) is reached. Given the narrower focus of the study, on successful commanding officers for RMCs and SUPSHIPs, saturation is reached after nearly a dozen interviews, indicating sufficiency in terms of the sample frame.

Findings and Conclusions

The study's findings are identified using a coding framework following Gioia et al. (1994), with a multistage analytic approach to data collection, analysis, and interpretation. The eleven interviews conducted generated over 300 pages of interview transcripts and notes, which generates nearly 500 first level codes, supporting the identification of 11 clusters at the second level of qualitative analysis. These clusters enable us to identify 14 issues, which we propose to address through ten alternatives or courses of action for consideration by EDO community leaders. Member checking supports the fidelity of our interviews and reasonableness of our findings.

For the most part, this set of issues and alternatives center on four key elements: 1) education, 2) training, 3) experience, and 4) mentoring. However, we also find 5) personality to represent an important contributor to command success. While the technical knowledge and expertise is as a necessary foundation, leadership is identified as central to successful command. At the O6 rank is often too late for first command, although mentorship and guidance can mitigate some of the challenges of the CO job for those who seek and cultivate these types of relationships. Officer in charge experience at RMC detachments prior to RMC CO can contribute to successful RMC command. The EDO COs provide not only technical, but also contractual and business oversight for Navy shipbuilding and maintenance contracts accomplished in the private sector. The education and training of EDOs is found to be lacking in business and management understanding. Prior RMC experience before command can be beneficial as well as management or business graduate degrees. Regarding talent management, there is an unclear path to flag for RMC commanding officers. To incentivize EDOs to consider RMC command, the community needs to consider the balance between providing opportunities for RMC-type experience prior to command with the need to avoid specializing too narrowly and limit the path to flag level. As is the case often in technical industries, engineers do not necessarily make the best leaders. While education, training, experience, and mentorship are important to ensure the success at RMC (and SUPSHIP) command, personality also plays a role, prompting the community to carefully consider the people who have the attitudes and personality traits that are likely to help them become successful to take on the RMC command jobs.

Recommendations for Further Research

The engineering duty officer (EDO) community critically supports the U.S. Navy's capabilities for design, acquisition and maintenance of ships and shipboard systems needed to continuously improve the ability to counter advancing threats. The EDOs provide on-site technical, contractual, and business oversight for Navy new construction shipbuilding, repair and modernization contracts accomplished in the private sector. The demands and complexity of EDO jobs have increased over time.

Future research is needed to test pilot implementation of courses of action for consideration by EDO community leaders to incentivize interest to take on challenging command and to increase the chance of success at command. Future studies can use a case study or policy evaluation approach to investigate relevant intended and unintended consequences of piloted changes and provide decision-support for scaling courses of action or policy changes that best support the needs of the community and align with its long-term strategy.

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NPS-22-N323-A: 1. Sailor Perspectives and Recommendations for Communication About Divisive Events and Inclusion within the Fleet

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Student Participation: CPT Annmarie McFadden USMC, LT Wesley Norton USN, LCDR David Machinporrata USN, LCDR Melanie Martins USN, and LCDR Cesar Valenzuela USN

Project Summary

Recent divisive events, at both national and global levels, have brought to light the challenges leaders in private and public/governmental organizations face when communicating with employees about sensitive events that may impact organizational effectiveness. The Navy's recent steps to engage in necessary conversations to address divisive events and leverage inclusion and diversity to fully promote warfighting excellence highlighted the challenges inherent in such communication and created the need to better understand how to help leaders engage sailors when divisive events arise.

This study uses a case analysis and a design-thinking approach to explore sailors' perceptions of conversations about sensitive events to identify tensions and strategies for advancing successful and needed conversations. The data for this study are collected through forty-four semi-structured interviews with sailors ranking E1-O6 and are analyzed using a qualitative approach via well-established inductive theory building methods.

The integration of the participants' responses with the related literature highlights four needed individual and organizational capacities to support successful conversations about sensitive subjects: metacognition, emotional regulation, cultural curiosity, and communication competence.

The study generates two key conclusions. First, sailors disagree on what topics require conversation: majority and minority groups' perceptions differ, and the inability to engage effectively in sensitive conversations is a military vulnerability. Second, the Navy communication often demonstrates an inadequate capacity for managing these conversations: leaders lack self-awareness, emotional regulation is challenging, cultural curiosity is not developed, and the tensions generated by communication hierarchies limit communication effectiveness.

To facilitate change, we recommend drawing from successful programs such as bystander intervention and "see something, say something" to encourage responses to exclusionary communication, emphasize cohesion, and recognize disinformation and division as a security threat.

Keywords: *inclusion, retention, current events, division, learning strategies, under-represented groups, diversity education, leadership*

Background

Earlier research highlights the potential positive effects of diversity and how diversity can enhance organizational performance (Shore et al., 2011). Most recently, researchers and leaders of organizations are seeking to fully integrate employees with diverse experiences and backgrounds into organizations by creating a sense of inclusion (Bilimoria et al., 2008; Roberson, 2006, Shore et al., 2011).

Consistent with current research findings, Navy leaders recognize that a healthy, diverse work culture is necessary to fully promote warfighting excellence. The Navy is comprised of individuals with a large diversity of backgrounds from many underrepresented groups based on geographical upbringing, occupational specialty, gender, sexual preference, commissioning source, race, ethnicity, and many other characteristics. This diversity presents a rich potential resource if all groups and individuals can be fully included in the organization.

However, recent divisive events at both national and global levels, have brought to light the challenges leaders in both private and public/governmental organizations face when communicating with employees about sensitive events and issues that are often tied to deep and long-held societal divisions.

The Navy's recent steps to engage in necessary conversations to address divisive issues have highlighted the challenges inherent in such communication. To create an inclusive workplace and take full advantage of the potential presented by its diverse workforce, the Navy requires a deeper understanding of sailors' perceptions of inclusion and exclusion and of ways to support naval leaders of diverse teams address negative experiences and divisive events.

This study builds upon previous research focused on the tensions between participation and organizational control in online workplace communities (Aten & Salem, 2020) and explored sailors' experiences of sensitive conversations and of necessary conversations by Navy leadership directly following the attacks on the U.S. Capital.

The study explores two research questions:

1. What are the perceptions, experiences and challenges identified by Navy supervisors and team members when responding to critical events that occurred from March 2020 through March 2021?
2. What training objectives and strategies could equip supervisors to address negative experiences/perceptions, bias/stereotypes, and barriers to retention?

This study uses a case analysis and a design-thinking approach to address the research questions. The main data collection effort is focused on forty-four semi-structured interviews with sailors at various ranks (E1-O6) to identify tensions and strategies for advancing successful and necessary conversations. The interview transcripts are analyzed using a qualitative analysis approach via well-established iterative inductive theory building methods.

Findings and Conclusions
The study's findings are identified using coding of semi-structured interviews of forty-four sailors across three genders, seven minority classifications and ranking E1-O6 using a structured analysis of key incidents using inductive theory building, resulting in theory and observation themes.

Our analysis of participants' responses to interview questions revealed four key implications and two major conclusions. We found that (1) participants do not perceive a strong connection between the recent Navy-instigated sensitive conversations and the warfighting mission, (2) there is a lack of agreement on what issues require Navy wide-conversation, (3) leaders are not equipped in terms of skills or personal characteristics to engage in sensitive conversations on all topics at all times, and (4) the organization is not fully equipped to get the most from these conversations.

These implications suggest two key conclusions. First, sailors disagree on what topics require conversation: majority and minority groups' perceptions differ, and the inability to engage effectively in sensitive conversations is a military vulnerability. Second, the Navy communication often demonstrates an inadequate capacity for managing these conversations: leaders lack self-awareness, emotional regulation is challenging, cultural curiosity is not developed, and the tensions generated by communication hierarchies limit communication effectiveness.

To facilitate change, we make several recommendations drawing from successful programs such as bystander intervention and "see something, say something" to encourage responses to exclusionary communication, emphasize cohesion and recognize disinformation and division as a security threat.

Recommendations for Further Research

This study uses a case analysis and a design-thinking approach to investigate perceptions of inclusion (and exclusion) and to identify learning strategies and jobs aids (such as vignettes) to train and educate supervisors of the diverse teams to address negative experiences/perceptions, bias/stereotypes, and barriers to retention and create and extend positive experiences.

Future research is needed to explore the impact of communication strategy tools inspired by successful programs such as bystander intervention and "see something, say something" on retention, development, and promotion of diverse units, as well as the impact on operational effectiveness.

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N2N6 - Information Warfare

NPS-22-N060-B: Cyber Warfighting System for Resilience and Response

Researcher(s): Scott Jasper, Sharon Runde, Victor Garza, Brian Wood, and Jason Altwies

Student Participation: SCPO Ben Shady USN, and SCPO Amaury Ponciano USN

Project Summary
The Cyber Warfighting System project aims to provide an automated capability to recognize and declare the threat to set appropriate resilience and readiness postures. Organizations use an incident response methodology to respond to and manage the effects from a cyber-based intrusion event. Rapid and accurate identification of intrusions and the implementation of adequate response methods to reduce the impact upon operations and recover system functionality and security quickly remain a priority for all organizations reliant upon digital networks. Identifying potential defensive gaps, constraints, and resource limitations during the execution of incident response remains a critical requirement for Department of Defense (DoD) organizations. In 2022, the Naval Postgraduate School (NPS) studied and analyzed the use of automated incident response between afloat units and ashore support.

Keywords: *resilience, response, cybersecurity, orchestration, automation*

Background
Today massive numbers of uncorrelated and unprioritized alerts overwhelm network security operations. A different approach is needed, one that can operate effectively at network scale and attack tempo against sophisticated techniques to defeat an adaptive attacker before damage is done while maintaining operations.

In 2020, NPS studied and analyzed cloud-based cybersecurity platforms that provide behavioral based detection techniques combined with machine learning algorithms. The findings and analysis are contained in the Master of Applied Cyber Operations (MACO) student capstone thesis (Roscoe, Sauerbier, & Rodriguez Reyes, 2020). Distribution of the thesis is authorized to DoD and U.S. DoD contractors only.

In 2021, NPS studied and analyzed cloud-based cybersecurity platforms that provide security orchestration, automation, and response capabilities. The findings and analysis are contained in the

Master of Applied Cyber Operations (MACO) student capstone thesis (Rucker & Hollingshead, 2021). Distribution of the thesis is authorized to DoD and U.S. DoD contractors only.

Findings and Conclusions

The findings and analysis are contained in the MACO student capstone theses (Ponciano, 2022; Shady, 2022). Distribution of the theses is authorized to DoD and U.S. DoD contractors only. They are also contained in a CUI/NOFORN Executive Summary and Technical Report. Distribution of both is authorized to DoD and U.S. DoD contractors only.

Recommendations for Further Research

The Cyber Warfighting System project will conduct a series of events to study and analyze alternative architectures, dataflows, and workflows for cyber defense of Department of Defense organizations.

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NPS-22-N157-A: Game Theory and Prescriptive Analytics for Naval Wargaming Battle Management Aids

Researcher(s): Bonnie Johnson, John Green, Scot Miller, and Arkady Godin

Student Participation: Bryan Lee CIV, Andrew Graham CIV, Jor-El Sanchez CIV, Rachel Badalyan CIV, and Michael Nixt CIV

Project Summary

To achieve and maintain decision and mission superiority, the Navy has prioritized research in computational technologies and data analytic methods for automating and improving battle management and decision-making. This project studied novel automated techniques using a multidisciplinary systems analysis approach and developed conceptual designs for automated wargaming systems to support tactical decisions and operational planning. The research approach revealed three different applications for automated wargaming: (1) to support table-top wargames as an automated white cell for adjudication or as a red team cognitive agent, (2) to support operational mission planners as a non-real-time course of action (COA) engine, and (3) to support the tactical warfighter as a real-time COA engine that considers second, third, and nth order effects as it evaluates and recommends possible tactical COAs. The study found that automated wargaming battle management systems (leveraging game theory, prescriptive analytics, predictive analytics, artificial intelligence, etc.) are needed to support enhanced situational awareness, reasoning, and problem-solving, faster decision timelines, and the identification and evaluation of tactical and operational COAs. The study recommends further research into the use of automated wargaming systems, the emerging field of course of action engineering, and the applications of these novel techniques to support table-top wargaming, operational planning, and tactical decision-making.

Keywords: *game theory, prescriptive analytics, wargaming, battle management aids, decision-making, artificial intelligence, data analytics, tactical warfare, operational planning, courses of action, predictive analytics*

Background

Game theory and prescriptive analytics offer two potential game changing capabilities for naval battle management superiority. Tactical operations can take a significant leap in progress with the aid of automated wargaming systems for real-time course of action (COA) decisions and for mission planning. Automated wargaming systems can predict the success of different COA options and consider possible second and third order effects. Future automated wargaming systems could accompany current development in the use of artificial intelligence (AI) to improve battle space knowledge and battle management.

The study leverages research in decision science, predictive analytics, AI, and causal inference. The study incorporated work being done in game theory, regret minimization and equilibria, counterfactual regret minimization, and recent experiments with AI systems playing games. The study drew upon methods and concepts for predictive modeling and influence diagrams. The study took a closer look at research that has focused on the application of these methods and capabilities in the military domain.

The Navy is taking advantage of advances in computational technologies and data analytic methods to automate and enhance tactical decisions and support warfighters in highly complex combat environments. Novel automated techniques offer opportunities to support the tactical warfighter through enhanced situational awareness, automated reasoning and problem-solving, and faster decision timelines. This study investigated how the Navy can use game theory and prescriptive analytics methods to develop real-time wargaming capabilities to support warfighters in their ability to explore and evaluate the possible consequences of different tactical COAs to improve tactical missions. This study explored data analytic methods including game theory, prescriptive analytics, and AI to evaluate their potential to design and engineer automated wargaming capabilities.

This study applied a systems analysis approach to develop conceptual designs of wargaming capabilities for real-time tactical decisions, for mission planning operations, and to assist table-top wargaming. A Naval Postgraduate School (NPS) student systems engineering capstone team studied the use of game theory and prescriptive analytics to generate requirements and develop a conceptual design for a real-time tactical wargaming decision aid (Badalyan et al., 2022). An NPS systems engineering thesis student developed requirements and a conceptual design for an AI-enabled wargaming system for mission planning (Lee, 2022). An NPS faculty researcher studied the use of AI and game theory to develop an automated wargaming capability to improve table-top wargames.

Findings and Conclusions

This study identified three battle management applications for future automated wargaming capabilities that leverage game theory and advanced analytics: (1) tabletop wargames, (2) mission planning, and (3) tactical decision-making. The study addressed the research objectives by first conducting a literature review of game theory, advanced analytics, and modeling environments that the Navy and other military services have created to date. The research team, consisting of NPS research faculty and systems engineering students, identified the three battle management applications. The team applied a systems analysis to two of the three applications: for mission planning and for real-time tactical decision-making. The team conducted a needs analysis and requirements analysis for each of these applications. Next, the team developed conceptual designs using model-based systems engineering tools to capture system and architectural design artifacts. The students developed names for each of the automated wargaming capabilities: the Strategic Operational Decision Aid for the automated system that could support future mission planning, and the Wargaming Real-time Artificial Intelligence Decision Aid for a future tactical decision aid. The team worked with researchers from the Naval Air Warfare Center China Lake to investigate the use of automated capabilities to support future table-top wargames as an automated adjudicating White Cell.

The NPS research team studied the operational need for a real-time naval wargaming battle management aid. The team drew upon former research that the principal investigator performed that characterized instances of complexity in military operations that result in situations that require automated decision support systems. Highly complex tactical military decision spaces can be characterized as having extremely short reaction or decision timelines; significant levels of uncertainty in situation awareness knowledge; extreme dynamics in the threat tempo in terms of heterogeneity, number, and kinematics; and information confusion with too little or too much information. Complexity in the military mission planning domain is also a candidate for applying an automated wargaming system. Military mission planning is currently a very manual and lengthy process. An automated system can identify and evaluate many more possible COAs than can be done manually.

The study's topic sponsor can use the findings of this research project as a basis for funding the research and development of automated wargaming systems. One step is to continue studying means of automating game theoretics as well as prescriptive and predictive analytics. Another step is to continue studying the three application domains to identify a manageable scope for some proof-of-concept demonstrations. The topic sponsor could use the foundational knowledge from this study to develop an automated wargaming capability road map for the Navy.

Recommendations for Further Research

The Naval Postgraduate School study team recommends that automated methods leveraging game theoretics, prescriptive analytics, and artificial intelligence continue to be pursued by the Navy for the three categories of applications identified in this study: (1) to provide white cell adjudication, game design support, and automated players for table-top wargames, (2) to support operational planners as a course of action (COA) engine to identify, evaluate, and recommend COAs, and (3) to support tactical decision-making as a real-time automated wargaming aid to provide predictive causal analysis to tactical COAs. The team recommends the following specific research initiatives as future work:

- Operational concept studies—to understand how/when, and under what conditions, automated wargaming decision aids are useful and even necessary
- Development of ontologies to support the three naval applications
- Development of red cell modeling
- Study of information and system architectures needed to support real-time tactical wargaming decision aids (what information needs to be shared, whether a centralized or decentralized distributed architecture are needed)
- Cross-domain studies to determine how automated wargaming systems can support multiple domain and multiple mission areas
- Bottom-up vs. top-down and general boundaries of the wargaming models and decision-making—are they necessary? Do they constrain solutions?

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NPS-22-N180-A: Indications & Warning for Amphibious Ops against Taiwan: Philosophy, Methodology, Applications, Results

Researcher(s): James Wirtz, Wade Huntley, James Russell, and Michael Malley

Student Participation: No students participated in this research project.

Project Summary
Meeting likely challenges in the Western Pacific will require the United States to generate forces, especially U.S. Navy units, in the region. Although Indications and Warning (I&W) intelligence is now central to current and future U.S. Navy strategy and operations across the Indo-Pacific, today's officers and intelligence analysts have limited experience with managing the I&W system in general or with I&W intelligence in particular. This research explored several potential warning scenarios in the western Pacific, identified likely efforts at denial and deception that could be used to mask force generation from observers, and described necessary courses of action to mitigate I&W failure. The analysis found that it is unclear if commanders understand the difference between I&W intelligence and intelligence reporting offering specific event predictions; confusion in this regard might lead them to disregard warnings in the expectation that more specific estimates are in the offing. The Office of Naval Intelligence should take responsibility for monitoring the status of the Navy's I&W system. Intelligence officers should monitor the synchronization of I&W realities with operational plans and necessities.

Keywords: *indications & warning Intelligence, I&W, surprise attack, deterrence, maritime deterring*

Background
The Department of National Security Affairs (at the Naval Postgraduate School) is eager to support the work of the Office of Naval Intelligence and the Office of the Chief of Naval Operations in particular and the U.S. Navy in general to meet the threat of great power conflict and geopolitical upheaval, especially as pertains to the maritime threat in the Western Pacific in its many forms. The U.S. Navy has responded to the People's Liberation Army Navy (PLAN) activities in the South China Sea and the Western Pacific, especially a series of so-called Gray Zone activities. Concerns about PLAN area denial and anti-access weapons and doctrine have accompanied the rise of these Chinese activities in the South China Sea, although these actions are part of a timeless cycle of adaptation and reaction between ship vs. shore-based combatants.

The ongoing threat posed by the People's Republic of China (PRC) is focused on a longstanding desideratum: gaining sovereignty over the island of Taiwan. Beijing regards Taiwan as a sort of breakaway territory, which it has vowed to control. There is no timeline set for this "reunification"—at the moment all parties (the PRC, United States, and Taiwan) still abide by it and acknowledge the “one country, two systems” principle, whereby all concerned recognize that Taiwan is not a separate “country” from China. By contrast, the residents of Taiwan tend to see themselves as an independent country, with its own constitution, democratically elected leaders and a military force of upwards of 300,000 soldiers, sailors and airmen and women. At the moment, the Democratic Progressive Party, which leans towards eventual official independence from the mainland, currently holds sway on the island.

In recent years, concerns have grown about the possibility that Beijing might take matters into its own hands by mounting some sort of operation to cross the Taiwan Strait and launch an amphibious assault against Taiwan. In early 2021, the PLAN and the People’s Liberation Army launched a series of air incursions into Taiwanese air space, suggesting that a Chinese invasion of Taiwan is an increasing threat. I&W intelligence detects changes in the operational posture of the opponent to warn that the possibility of dangerous or otherwise unwanted activity is growing. I&W provides a risk assessment to warn military forces to move to a heightened state of defensive alert and that the time has arrived to take action (Belden, 1977).

The purpose of this research is to explore how I&W intelligence can help bolster deterrence in the Western Pacific. The research discusses three scenarios to illustrate how they each present a unique set of I&W requirements. It also explores the various stratagems that might be adopted to complicate the efforts of I&W analysts to generate warnings and associated efforts to help commanders develop accurate situational awareness during a crisis. The research then addresses I&W intelligence as a system, identifying issues that can prevent both intelligence analysts and commanders from playing their designated parts.

Findings and Conclusions

Three “scenarios” regarding Taiwan in the Western Pacific suggest themselves as targets for I&W intelligence: conventional I&W, Gray Zone activities, and accidents.

Senior officers have “grown up” in a world in which U.S. forces enjoyed command of the sea and air in any given theater of operations, giving them an opportunity to project power ashore, maintain unfettered logistics, and to deny the opponent an opportunity to wreak havoc on U.S. interests and allies in the region. They also enjoyed their ability to “command the sea” without little need for indications and warning intelligence. The U.S. Navy could deal with most challenges with forces in-theater on a day alert, peacetime status. Senior Navy commanders always saw their intelligence officers as an important source of information, but it is not entirely clear if they also served as an important source of warning. Today this is no longer the case.

The analysis found that it is unclear if commanders understand the difference between I&W intelligence and intelligence reporting offering specific event predictions; that is, operators might disregard or misinterpret I&W intelligence because they expect intelligence analysts to provide detailed predictions of impending action undertaken by the opponent.

To be effective, I&W intelligence needs to exist as a system that links together analysts and operations, warning and response, intelligence realities to strategic and operational requirements. The research found that the failure to create this system is a universal cause of intelligence failure, facilitating surprise attack. Intelligence analysts and managers need to take responsibility for this "system." Analysts and operators need to take steps to create an I&W system to bolster deterrence in the Western Pacific.

Recommendations for Further Research

The Naval Research Program should sponsor a workshop on Indications and Warning (I&W) as a system to bring together scholars, intelligence analysts and operators. Recognizing I&W as important and treating I&W as a system raises important questions that are directly related to the effectiveness of U.S. deterrence across the Indo-Pacific and the availability of credible combat capability during a nascent crisis. For example, should the Office of Naval Intelligence take responsibility for monitoring the status of the Navy's I&W system? Should intelligence officers monitor the synchronization of I&W realities with operational plans and necessities? Who is going to take responsibility for rebuilding the Navy's I&W system after a thirty-year strategic and intelligence hiatus through ongoing training, education and research?

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NPS-22-N184-A: Joint All Domain Command & Control (JADC2) Naval Analysis

Researcher(s): Mark Nissen, and Shelley Gallup

Student Participation: LT Erik Locke USN, and LT Austin Prettyman USN

Project Summary

Joint All Domain Command and Control (JADC2) is the art and science to rapidly translate knowledge and information into decisions and actions. It seeks to integrate all services across all warfare domains and through all communication environments. The research described in this report works toward JADC2 conceptualization from a Navy perspective. A comparative case study is used to analyze command and control (C2) for a maritime focused joint task force (JTF) involving integrated fires and grey zone operations across services. Key results highlight the importance of satellite communications to enable JTF

integration, and they elucidate a matrix of critical communication links that emerge in environments of denied, degraded, intermittent or limited (DDIL) communication. This DDIL communication matrix serves as a prioritized JADC2 requirements set. Recommendations center on prioritizing these requirements; articulating and disseminating clear command intent that can be understood and implemented in DDIL environments; practicing Mission Command, Battle Rhythm Dilation, and Edge C2; remembering that people remain the most important element in JADC2; and developing the new knowledge, education, training, and practice necessary for JADC2 success.

Keywords: *agile C2, command and control, C2, rapid reconfiguration, knowledge flow, joint all domain command and control, JADC2, mission command, battle rhythm dilation, Edge C2*

Background

JADC2 seeks to address the many challenges of C2 across all domains and services, but it requires thoughtful conceptualization, especially from a Navy perspective. A comparative case study is used to analyze C2 for a maritime focused JTF involving integrated fires and grey zone operations across services. The baseline case represents a geographically distributed carrier strike group (CSG), surface action group (SAG), Air Force (AF) wing, and Marine expeditionary force (MEF) operating jointly, through conventional C2, with full communication capabilities. The comparison case depicts this same JTF without satellite communications.

Comparative analysis across these cases exposes many C2 challenges and helps to conceptualize how JADC2 must support both operational and tactical levels of war, along a continuum of communications capabilities. This analysis also provides insight into elements of C2 that extend well beyond technology; particularly the people, processes, and organizations comprising the JTF; along with the knowledge, information, and data that must flow to interconnect them.

The analysis enables us to apply theory representing the state of the art and to draw from tools and techniques representing the state of the practice in knowledge management, organization, and C2 to JTF organizations and operations. This enables us also to induce new knowledge from analysis of JTF operations, which offers potential for translation into enhanced and refined Navy C2 organizations and approaches.

Findings and Conclusions

Key findings highlight the importance of satellite communications to enable JTF integration. This applies in particular to geographically dispersed services seeking to interoperate in an integrated manner. Further, a matrix of critical communication links emerges through analysis of DDIL environments. This DDIL communication matrix serves as a prioritized JADC2 requirements set.

Interestingly, respective Navy, Air Force, and Marine tactical operations within the CSG and SAG, AF wing, and MEF do not suffer as greatly in DDIL environments as their joint and operational counterparts seeking integrated fires and operations across services. Details remain beyond the classification level of this document.

Additionally, the prioritized JADC2 requirements set involves much more than technology. Indeed, commanders at all organization levels need to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments, and subordinates at all levels must be able to understand and translate such intent into desired actions. This requires practice: Commanders at all organization levels and units at all levels need to practice operating under Mission Command and Battle Rhythm Dilation, for extended periods of time, much as the way that integrated submarine operations do. Moreover, these commanders and units need to practice integrated operations through very low bandwidth DDIL communication modes, which elucidates a compelling case for Edge C2.

Finally, people remain the most important element in JADC2. Geographically dispersed joint operations in DDIL environments can depart substantially from the kinds of education, training, and experience that most military personnel encounter. This provides a use case for additional education, training, and experience to develop and refine the necessary skills and competencies required to fight effectively.

Moreover, such operations can prompt the rethinking of standard operating procedures (SOPs); techniques, tactics, and procedures (TTPs); operational orders (OPORDs); and similar explicit knowledge. The key is to anticipate, develop and refine the kind of rich, experience based tacit knowledge that needs to permeate all organization levels from deckplate to command. Such tacit knowledge—once acquired and refined—can guide effective rethinking of SOPs, TTPs, OPORDs, and similar documents.

Navy educational institutions like the Naval Postgraduate School (NPS) represent one important locus for rethinking along these lines, as do tactical training groups: NPS can develop and teach the appropriate knowledge, which tactical training groups can translate into effective procedure and practice. **This may represent the most important finding for our study sponsor: new knowledge, education, training, and practice are necessary for JADC2 success.**

Five recommendations follow accordingly:

1. Use the Communication Matrix to prioritize JADC2 requirements that emerge from this study.

2. Teach and coach organization leaders to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments over extended periods.

3. Learn and practice both Navy and joint operations through Mission Command, Battle Rhythm Dilation, and Edge C2.

4. Remember that people remain the most important element in JADC2.

5. Develop the new knowledge, education, training, and practice necessary for JADC2 success, both through continued study along these lines and through new education and training course development.

Recommendations for Further Research

We have five recommendations for further research.

1. The Communication Matrix indicates the key communication links required for effective joint task force (JTF) knowledge and information flows across service, unit, platform and geographic boundaries; and it shows which are affected most severely by denied, degraded, intermittent or limited (DDIL) communications. This provides an opportunity for each link to be studied more deeply—in terms of associated people, processes, organizations, and technologies.

2. Teaching and coaching leaders to articulate and disseminate clear command intent that can be understood and implemented in DDIL environments over extended periods should begin with dilation of the JTF battle rhythm. DDIL may require JTF commanders to receive knowledge and information inputs less frequently, with proportionately longer periods between opportunities to direct and guide subordinate commanders and units. Training and practice will be essential. This provides an opportunity to develop the corresponding courses and exercises.

3. Mission Command is likely to be understood relatively well, but it remains unclear how frequently and persistently it is practiced in the fleet and across services. With less frequent knowledge and information exchanges, the JTF—and most subordinate commands—will encounter Battle Rhythm Dilation, and commands at different hierarchic levels will likely follow different rhythms. For commands and forces accustomed only to a 24-hour rhythm, this may require considerable adjustment and practice. This provides an opportunity to develop the corresponding courses and exercises.

   Alternatively, Edge C2 is less likely to be understood well, yet it is crucial for commanders and units to integrate operations through very low bandwidth DDIL communication modes. The C2 field has accumulated over two decades of research regarding Edge C2, but surprisingly little of the corresponding knowledge has found its way into Navy doctrine and training. This provides an opportunity to develop the corresponding courses and exercises.

4. It is both easy and routine for a project like JADC2 to degrade into a portfolio of technology efforts. However, JADC2 has a very long way to go before the Sense-Make Sense-Act cycle can be automated (if ever). This applies in particular to the latter two steps: decision makers and other people have to make sense of situations, while warriors and other people initiate and execute the

associated actions. The faster that cycles become—speedy cycles represent an express JADC2 expectation—and the worse that DDIL restrictions become—severe environments represent an express JADC2 expectation—the more challenging each step of the cycle becomes. This provides an opportunity for further study.

5. Each of these recommendations for further study points to knowledge gaps. Some gaps (e.g., 2 and 3) are relatively clear and can be filled through development of additional education and training courses, along with corresponding exercises and practice, whereas others (esp. 1 and 4) are less clear and require further study.

References
Included in technical report

NPS-22-N270-A: Expeditionary Domain Awareness - Intelligence Support to NECC & NECC Support to Intelligence Analysis (NECC focus)

Researcher(s): Arijit Das, Neil Rowe, Walter Kendall, and Peter Ateshian

Student Participation: Aroshi Ghosh

Project Summary
The Navy Expeditionary Combat Command (NECC) community gathers information and intelligence documents that accumulate over time on file stores. The intelligence consumers needed a method to search all prior knowledge documents, preferably based on common language keywords and phrases. This challenge could be solved by working with an existing vendor product with the associated licensing, support, and maintenance. The Naval Postgraduate School (NPS) team took a computer science (CS) approach to identify the various workings of a document store/search portal (system). An evaluation of each technology step involved was conducted, and potential solutions and their associated costs were considered. The team found that given user specifications, a tech-savvy team, and combined with open-source and Department of Defense (DOD)–licensed software, one can build and maintain a system that meets the requirements of the Department of Navy (DON) community.

Keywords: *naval expeditionary combat command, NECC, expeditionary domain awareness, intelligence, operations, collaboration, portal, information stream, naval expeditionary combat forces, tribes, database, hadoop, artificial intelligence, machine learning*

Background
The initial understanding was that the NPS team would be given raw datasets to evaluate and analyze. After several meetings with NECC, it became clear that data is preprocessed and summarized in the form of reports. Reports can be in any format, namely Adobe Acrobat PDF, Microsoft Word and PowerPoint, images and plain text. These reports are distributed to the community via email/file systems and need to be searched later. There is no centralized system to store, analyze, and generate analytics (based on the documents) for the community.

One option was to evaluate vendor content management systems (CMS) applications, but instead the NPS team looked at the challenge with a computer science mindset. The team had prior background with processing large datasets and extracting analytics using the Hadoop Distributed File System (HDFS) and a relational database. Common algorithms/code focus on plaintext; since the NPS team was familiar with processing binary files and extracting needed information in plaintext, this could be applied to the non-plaintext documents. Data growth is an important consideration that should be handled with technology seamlessly. For this the NPS team used its background in Big Data technologies with HDFS.

After documents were loaded into the system, algorithms had to be researched that could extract the keywords in plaintext and create metrics. These metrics will help in intelligent results when the user community searches historical information with keywords and phrases. The NPS team used its background in document classification to evaluate algorithms that worked.

For any such system to be viable, the user community needs a friendly user interface. There is also the challenge of multiple devices like a laptop, desktop, handheld devices, and phones. The NPS team looked at openly available technologies like HTML5, JavaScript, open-source webserver, and Python programming libraries. The frontend (browser on laptop/phone) needs to send data over the internet to a webserver (middleware) that is subsequently sent to the database (Oracle) backend. For all of this to work, the three parts need to be compatible.

Overall, technologies need to be available via DOD licensing and be cost effective. The plan was not to recommend any esoteric or custom software that might be a financial challenge and face lack of developer community support. Instead of total reliance on vendor consulting teams, these technologies must be supported by DON in-house technology teams with training and minimal vendor support.

Findings and Conclusions
The NPS team started with building a sandbox to evaluate the possible technologies. For the document store that can scale up, it considered the Oracle vendor database product. Using the Oracle XE laptop version, the team loaded documents and wrote SQL to query them. In the sandbox, NPS used the laptop version with the assumption that a production Oracle database will work with the same codebase as the laptop version.

In the studied system, keywords need to be extracted from the documents. While it is easy to achieve this with plaintext, with binary format documents, the solution is to use optical character recognition (OCR) technology. The first step is to convert the documents to image format and then use the OCR application to extract the keywords. Extracted keywords need to be cleaned of punctuation marks and stop-words (words used for grammatical sense) and lemmatized (variations of a word need to be made one). All final extracted words are stored along with the original documents, thus the database handles binary and plaintext datatypes.

For each document loaded, the keywords are used to create a matrix using term frequency-inverse document frequency (TF-IDF) vector algorithms. To calculate distance metrics, the cosine similarity algorithms are run on the matrix. Distance metrics are critical when the end users search for documents using keywords and phrases, as they will help generate a list of documents that are closest to the search string.

The team evaluated the frontend on a laptop using a browser. The middleware is from Flask (open source application server), which is a Python programming language product. Flask lets one build the full software application in Python, so all the algorithms are Python packages that can be deployed to the Flask webserver, and use the database as a store. When the frontend was deployed on an Android phone, it uses the Java programming language while Flask uses Python. A workaround is to use a Java to Python connector Jython, which lets Java applications to use Python libraries/code. This is an extra layer of software that can increase execution time and will degrade speed of execution with data growth.

The system studied by the team requires that each time a document is loaded, all the calculations have to be redone; this can be a challenge when the number of documents start to grow. The sandbox did not fully test data growth using a HDFS system.

Initial reports were sent to the topic sponsor, and their results were encouraging. The study has raised awareness of the problem, and the full report will be sent next. More research needs to be done before this idea can be implemented into production.

Recommendations for Further Research

The NPS team studied the document store/search system on a laptop sandbox, so a next step will be to be scale up the evaluation. A server-based system can be used with a HDFS backend to understand the challenges of large-volume execution. A repository of datasets in the terabyte range will be a more realistic test of the system. The middleware technology needs to work on all platforms—if it works on Python and not on Java means a more generic middleware architecture needs to be researched and evaluated. Frontend technologies need to be looked at on a wide range of devices with large user community involvement. The middleware architecture needs to handle user growth for loading/searching of documents, thus more options beyond Flask need to be evaluated.

Additionally, there are many DOD CMS vendors who can be reached to present their solutions and evaluated. More studies need to be done with other DOD entities that may have already solved this problem.

References

None

NPS-22-N271-A: Long Range Fires in Degraded and Denied Environments

Researcher(s): Eugene Paulo, Douglas MacKinnon, Wayne Porter, and Paul Beery

Student Participation: Muhammad Anwar CIV, Luis Gonzales-Velazquez CIV, Matthew Murphy CIV, and Raafay Qureshi CIV

Project Summary

The employment of long-range fires is a high priority for the U.S. Navy, addressing the capability of forces to coordinate deep strike weapons that can be launched from an array of joint assets against critical enemy assets at sea or hardened facilities on land. Additionally, the long-range fires process must be resilient in a degraded or denied environment. However, coordinating long-range fires encompasses a complex set of actions to include target prioritization and development, command and control, tasking, kinetic and non-kinetic fires, battle damage assessment, rearming, and contested logistics. Our approach leverages recent Navy-sponsored research, simulation, and analysis to include projects involving joint fires within distributed maritime operations and feasibility of deploying hypersonic missiles on U.S. surface ships. We apply a similar approach here but augment it with a system of systems analysis of long-range fires in a degraded and denied environment as part of a timely and relevant joint operational scenario. We examine significant design decisions and operational parameters, as well as appropriate measures of effectiveness, in generating successful long-range fires through systems architecture development and simulation analysis. Based on the functional hierarchy and the primary variables, our simulation results show that the addition of decoys along with the long-range fire weapon salvo is more effective at successfully destroying the Red Force target compared to adding more weapons to the salvo. The decoys are capable of reducing the amount of command, control, communications, computers, intelligence, surveillance, reconnaissance, and targeting (C4ISRT) degradation, which results in a higher probability of hit and kill for the Blue Force weapons. Additionally, considering the cost of decoys versus weapons used, including cruise missiles, sea-skimming missiles, and hypersonic missiles, it can be more cost effective to use more decoys with the weapons salvo than adding more long-range fire weapons to the salvo.

Keywords: *long-range fires, hypervelocity missile, denied and degraded environment, counter command, control, communications, computers, intelligence, surveillance, reconnaissance, targeting, C4ISRT*

Background

Long-range fires involve launching ballistic missiles, cruise missiles, hypersonic missiles, decoys, flares, and electronic warfare weapons from multiple, extremely dispersed locations against critical enemy assets at sea or hardened facilities on land. The long-range fires process must also be resilient in a degraded or denied environment. The integration of long-range fires clearly meets the Navy's priority of All Domain Fires, and when including the need to apply these fires in a degraded environment, it also directly addresses the Navy priority of C4ISRT. Degraded communications can negatively impact the effectiveness of the weapons being used by the U.S. and jeopardize mission success. It is, therefore, necessary to assess how the U.S. can launch a combination of legacy and newly developed weapons to penetrate a denied territory within a degraded communications environment. Additional systems used in the mission scenarios include decoys with jamming capabilities and flares to obscure and offset enemy sensing capabilities. This combination of weapons is launched against targets composed of critical enemy assets located at sea or hardened, land-based facilities. A simulation of four related scenarios examines the success rate of various combinations of long-range fire weapons for striking targets within degraded or denied C4ISRT environments. For simulation purposes, the degraded environment means that C4ISRT capabilities for the deep strike weapons are reduced by up to 40% and 60% for denied environments.

The scenarios involve friendly forces' intelligence, surveillance, and reconnaissance (ISR) assets, revealing that the enemy is installing a long-range hypersonic missile launcher on disputed territory. This site has the capability to launch an attack on friendly or partner nation naval or land targets including major cities or military locations. Friendly forces, led by the Navy, have been directed to eliminate the proposed enemy launch site before it becomes operational and a threat to strategic interests. While four top-level system functions are defined, this research focuses its efforts on assessing battle damage under executing command and control (C2) and the two lower-level functions, selecting weapons and fire weapons under engage contact of interest (COI), which is decomposed from the employ weapons function. The primary measure of mission success is the measure of effectiveness (MOE) of probability of kill, which determines the percent chance the friendly force long-range fire weapon renders the enemy target destroyed so it cannot be used to launch any weapons.

Findings and Conclusions

Our primary research objective was to determine significant design decisions and operational parameters necessary to generate successful joint long-range fires in a degraded or denied environment against critical enemy assets at sea or hardened facilities on land. We sought to determine the potential increase in probability of kill by adding more long-range fire weapons to an attacking salvo compared to the potential increase in probability of kill using decoys along with the weapon salvo.

There are several system design variables that affect the success of friendly long-range fire weapons such as probability of hit or kill. For our simulation, we focused on the operational variables that can be adjusted by the mission commander including the number of weapons per salvo or the number of decoys used along with the weapon salvo. The percentage of C4ISRT available to the friendly forces (the objective is to make that percentage as high as possible) is a variable used in the simulation which is reduced due to the enemy target located within a degraded or denied environment, but that reduction can be mitigated with the addition of decoys.

Based on the functional hierarchy and the primary variables, our simulation results show that the addition of decoys along with the long-range fire weapon salvo is more effective at successfully destroying the enemy target compared to adding more weapons to the salvo. The decoys can reduce the amount of C4ISRT degradation caused by the enemy, which results in a higher probability of hit and kill for friendly weapons. Additionally, considering the cost of decoys versus weapons used, including cruise missiles, sea-skimming missiles, and hypersonic missiles, it can be more cost effective to use more decoys with the weapons salvo than adding more long-range fire weapons to the salvo.

Recommendations for Further Research

For future research, we recommend creating a higher-fidelity simulation model. Adding more variables to refine the scenarios and simulation such as specific weapon reliability, number, and types of targets, target distances, target speeds, and distance between friendly weapons and enemy targets in addition to specifics of counter command, control, communications, computers, intelligence, surveillance, reconnaissance, and targeting (C4ISRT) assets could provide a greater understanding of the complexity of long-range fires in a denied or degraded C4ISRT environment.

We also recommend modeling two excursion scenarios that includes the employment of unmanned aerial vehicles (UAVs) and flares. While the UAVs could provide a range of benefits to the friendly force, the flares could reduce the enemy's ability to track and destroy friendly targets.

Finally, the inclusion of real-world data (such as weapon and target attributes) would provide more realistic results. However, this is undoubtedly classified data and would result in the project having to follow classified guidelines.

References

None

NPS-22-N279-A: Naval Integration into Joint Data Strategies and Architectures in JADC2

Researcher(s): Arkady Godin, and John Green

Student Participation: No students participated in this research project.

Project Summary

This effort is focused on a study to apply key aspects of a data strategy developed earlier for the Naval Operational Architecture (NOA) to Joint All-Domain Command and Control (JADC2) knowledge strategy for joint warfighting at the tactical edge and higher-level tiers (i.e., operational, strategic, and national).

A major problem that, prior to this study, was unaddressed, is a lack of a model-based definition of a "situation" which is a key term in a battlespace necessary for collaborating participants to gain shared Situation Awareness (SA) across Title 10 intelligence and Title 50 Services.

A method used to address significant "abstraction level" gaps between observations and concepts at any level of conceptual abstraction relies on the availability of "knowledge representation," based on well-known principles of "Bayesian and Markov" Logic Networks and by utilizing graph model as an appropriate facility for persistent modeling and reasoning.

JADC2 imposes another challenge, which is auto-generation of contextual knowledge customized for mission-centric, collaborative, cross-organizational roles at any level of organizations' abstractions. A net result of auto-generation would be availability of actionable knowledge leading to actionable understanding.

JADC2's principal knowledge strategy conclusion is a need to apply causal inferencing at the very foundation of interdisciplinary areas of knowledge to drive any decision based on causal relations.

We recommend to blend "machine automated situations" with "human manual situations" as a natural progression for moving from "Asset Maneuver-to-Engagement Battlespace" domain workflow construct to organic "Human-Machine Teaming" (HMT) decisioning domain workflow construct. Therefore, a desired effect for JADC2 domain is to insert decision-makers into the HMT workflows.

Keywords: *Naval Operational Architecture, Joint All Domain Command and Control, joint warfighting, knowledge strategy, tactical edge, tiers, operational, strategic, national, situation, knowledge representation, contextual knowledge, abstraction, logics, orchestration, human-machine teaming, maneuver, engagement, reverse engineering, workflows, decision making, cross-organizational roles*

Background

The purpose of a study is in relation to the Chief of Naval Operations (CNO) and Joint Staff JADC2 organizations on defining operational requirements supported by scalable enabling infrastructure with great attention to the needs of the tactical edge. While Joint Staff Command and Control (JS J6) views JADC2 as a top-down enterprise, the research team argues JADC2 must be bottom-up, as operations at the tactical edge shape the rest of the enterprise. Our study views tactical edge operations as dependent on the ability of metadata catalog to capture the dynamic nature of the metadata. Our study is agreeable with the Topic Sponsor's concern that a metadata catalog is inadequate to handle the dynamic nature of metadata for Navy and JADC2 Joint operations.

However, our study concludes that, in addition to metadata being dynamic, something more fundamental is happening at the tactical edge. One of the principal conclusions of our study is that each executable mission undergoes a multiple change of states in the world model, resulting in different contexts. Therefore, a context-unaware metadata catalog is unable to distinguish if intersecting metadata belong to any particular context.

The results of the study are expected to greatly aid the mission accomplishment because a new type of data catalog would be capable to organize knowledge by context and, therefore, situations as they exist in their specific context. This natural separation between situations, which changes its context in time and space, will expand a knowledge of the situations to provide a greater SA to the decision makers. CDC will be capable of explaining what actually changed a context in a particular situation.

The study's methodology uses causality by positioning it at the foundational layer. We have concluded causal linkage based on "root – cause analysis" is the only possible methodology to identify situations, a prerequisite for obtaining the SA in an adaptive manner in highly-volatile operations, which is the case for JADC2 operational environments. Our original expectation of a need to detect novel situations led us to understand the criticality of knowing the context, which can be computable. Our team's hypothesis was based on deep understanding of a knowledge strategy, based on connected concepts of situations and their contexts.

This hypothesis has crystallized a need to abandon traditional metadata catalogs in favor of a "contextual data catalog." Such a prediction resulted in creation of a critical CDC criterion. This realization also forced our team to undertake a quest for commercially available CDC. It was a pure joy to find out one of the leading domestic companies in the United States just announced availability of "contextual data catalog" in October 2022. It was revealing that their major customers are start-ups, focusing on highly innovative products requiring highly adaptable and flexible data catalogs. This study helped to identify a fundamental requirement to overcome numerous JADC2 mission challenges.

Findings and Conclusions

The findings of our research study confirm, in full, our original expectations that JADC2 operational environment requires a development of a Joint Mission umbrella platform integrated with services, agencies and coalition partners. Hypothesis regarding Situation Awareness doing what it advertised turned out to be a myth. The long-term implication of our findings is the need to have a persistent monitoring of a myriad of dynamically changing situations in the chaotic battlespace. A related long-term implication is a need to persistently manage a "context" within the scope of discovered novel situations. The complexity of understanding and computing the context is heavily dependent on the heterogeneity of contributing knowledge types, including multi-media, scientific models, and such adaptive contributors as situation and workflow graph models. One of our study's principal realizations was a need to introduce flexible summarization engine capable of acting as a container and capable of imbedding the above-listed knowledge constructs to reflect the state of the world model at any time. The concept of imbedding must be based on different types of knowledge representations required to do the reasoning, utilizing heterogeneous generic and specialized logics necessary for JADC2 missions.

During the last five years, Joint Staff Futures Intel Branch was evolving "Cogent Way" (CW) project of digital modernization of JADC2 and Intel community to aggregate and reason over knowledge. Our research team at NPS and NAVWAR plays a "Research and Assessment" role for CW. We aim to further extend semantic web knowledge by inserting valuable abstractions (e.g., causal logic to detect situations and context) and key ML/AI integrations (e.g., neuro-symbolic learning and reasoning). Our goal is to extend semantic web "deep-shallow" reasoning with more powerful logics due to their specialization. Our study includes technology evaluation of technologies which suggest product development of the abstractions we find valuable. For example, this includes evaluation of world.data "contextual data catalog" as a metadata catalog replacement across JADC2 tiers. The latter is a legacy approach which may not take JADC2 where we want it to go. However, we will continue evangelizing concepts of situation and context for "engagement" and "decision" adaptive workflows. In the future, we would like to see an alignment between workflow knowledge strategy and architectures with the state-of-the-art dissemination like Communication-as-a-Service (CaaS). Our research team can see multiple benefits from embracing aggregation-by-summarization principle with graph embeddings as the future frameworks for the next Generation Command and Control. The other potential benefit, which could be revolutionary on its own merit, is applying dynamic context to just-in-time adaptivity of situations and workflows. We, at the NPS and NAVWAR, would be excited to participate in semantic web knowledge representation and reasoning being extended with more powerful knowledge representation and reasoning logics. Programmable logics show a promise but require further research in determining its applicability. Our research believes in a transformative power of causality to detect novel situations and, even, utilize causality as a methodology to develop optimal Course-of-Actions (COAs). Finally, we witness a potential by applying multi-dimensional dimensional hierarchical cubes for modeling joint sub-organizations.

Recommendations for Further Research

The focus of our research study has been on support complex ad-hoc composable Joint missions which is a major requirement of the Joint All-Domain Command and Control (JADC2) super-domain. JADC2 domain is a conglomerate of inter-operating domains using different vocabularies based on different taxonomies. Making such diverse commands, comprised of DOD services, Intel agencies and Coalition partners, to interoperate is a complex semantic undertaking.

“Cogent Way” project is a good example of what it takes to get a “knowledge and understanding” research taking off. We recommend providing a necessary funding for the “Cogent Way” data and knowledge strategy and implementation bold initiative. We understand it’s not going to be easy to get such project funded outside of utilizing “in kind” money. However, we need a baseline for advancing the knowledge strategy. Otherwise, it is hard to quantify whether the real progress in knowledge accumulation is occurring.

For further research, we recommend taking a deep look at logics: from well-understood semantic web logic to more exquisite logics like situation logic, event calculus, causal logic, action logic and even geo-spatial quantification logic. Our goal is to understand the realms of possible for such poorly understood areas in the DoD and Intel agencies as causality and its value for Situation Awareness and decision-making in obtaining knowledge of Blue Forces and COAs for the Blue and for the Red. If we start realizing a value of the context, we should strive to identify technologies that be generalized to catapult from data to knowledge above. Therefore, we should investigate existing graph-based metadata catalog technologies and identify which ones could be promoted to be “contextual knowledge” catalogs for the future. We should not be satisfied by staying at a data level and not being able to advance towards knowledge and understanding. Technologies from companies like “data.world” are good examples of thinking of innovations by inventing the abstractions.

There is a clear need to further invest into semi-automation and automation of processes. Considering partially- and fully automated workflows are advancing adaptation and allocation of resources to the execution of workflows, we must invest into the thinking on how “engagement” class of workflows collaborates with “decisioning” class of workflows. Significant attention should be brought to bear on how to we discover which workflows should be collaborating with chosen others to avoid having gaps of knowledge in knowledge acquisition. We should not discount plausible dependency between adaptive workflows and dissemination strategy and architectures. Should we invest in contextual adaptation to deliver the knowledge for decision-making with greater efficiency?

Utilization of logics is significantly unexplored area. The DoD and Intel Agencies, together with coalition partners, should bring logicians for collaboration to ensure the goals on keeping “data-information-knowledge-understanding-wisdom” (DIKUW) “in-situ” could be accomplished by choosing canonical knowledge representation. It is such representation of logical knowledge equations that would support different specialized logics with a single knowledge representation capable to transform itself to express knowledge equations required by different specialized logics.

References

None

NPS-22-N305-A: Considerations for Cross Domain / Mission Resource Allocation and Replanning

Researcher(s): Bonnie Johnson, Arkady Godin, John Green, and Scot Miller

Student Participation: Bryan Lee CIV, Tara Sprinkle CIV, Kelly Tesch CIV, and Christopher Ghigliotti CIV

Project Summary

This research project explored emerging innovative data analytic concepts and techniques (including game theory, machine learning, and wargaming) to effectively manage and allocate warfare resources across multiple domains to address multiple missions in dynamic operations. The research team identified and characterized complex tactical situations in which multi-missions need to be prioritized and dynamic replanning is required. The team developed a conceptual approach that leverages advanced data analytics, game theoretics, wargaming, artificial intelligence (AI) and machine learning (ML) to support and enable decision-making (to best use and allocate warfare resources and forces) during those complex tactical situations. The team developed model-based systems engineering representations of the conceptual design and modeled use case scenarios involving complex tactical, operational, and strategic situations. The team envisioned and modeled an innovative wargaming decision aid to support operational level mission planners that may encounter similar complex situations requiring a dynamic cross-domain multi-mission approach at this higher level.

Keywords: *multi-mission, cross-domain, resource allocation, dynamic replanning, complexity, game theory, machine learning, wargaming, data analytics, artificial intelligence, courses of action, battle management aids, mission planning aids, system analysis*

Background

A challenge in warfare is the ability to plan and implement warfare assets (platforms, systems, forces) to best meet mission demands. This endeavor is highly complex given multiple (and often competing) missions, limited resources, the organizational command structure, doctrine/rules of engagement that must be followed, dynamic changes in the operational situation, adversaries with their own strategies, and uncertainty and incompleteness in situational awareness. This historical challenge has always accompanied warfare. The question now becomes—what insights can advanced data analytics provide to enhance the warfighter's ability to optimally plan and implement warfare assets to meet military mission demands?

Effective cross domain and multi-mission resource allocation must consider the following four challenges: (1) integrating strategic and planning level decisions with tactical decisions that are immediate and often reactive in nature, (2) optimizing warfare resources hierarchically across multiple cross domain missions, (3) optimizing warfare resources under dynamic conditions (dynamic replanning), and (4) making decisions under uncertainty.

Striving to develop military strategies, plans, and tactical courses of action (COAs) that optimize across domains and missions and can adapt to dynamic situations will be necessary to maintain superiority in future complex conflicts. This project studied three specific innovative data analytic methods that offer potential solutions to this challenge: game theory, machine learning and wargaming.

This study supports the goals of OPNAV N2/N6 Information Warfare through exploration of innovative methods and concepts that enable and enhance decision superiority in tactical warfare, mission planning, and strategic operations. The results of this study inform research and development efforts for battle management aids and mission planning systems of the future. The study provides further understanding of the problem domain and insights into the application of AI, ML, game theory, and wargaming as solution capabilities. The study applied a systems analysis approach that included (1) discussion with the sponsor, stakeholders, and experts; (2) literature review; (3) participation in related workshops and symposia; (4) development of use case scenarios; (5) development of model-based systems engineering artifacts to represent system views, conceptual designs, and architectures; and (6) assessments of requirements, concepts, and scenarios. The research was performed by Naval Postgraduate School (NPS) faculty researchers, a systems engineering capstone team, and a systems engineering thesis student. The researchers and students had frequent communication with the research sponsor to elicit feedback and provide references and guidance.

Findings and Conclusions

This study produced findings in three general areas: (1) the characterization of complex tactical situations where cross-domain multi-mission operations are required, (2) the need for mission planning, dynamic replanning, and tactical decision-making that can address these complex situations, and (3) concepts for leveraging advanced data analytics to provide automated planning and decision aids for these applications. The study addressed the research objectives by first conducting a literature review of mission planning, tactical decision-aids, advanced analytics, game theory, and artificial intelligence. The research team, consisting of NPS research faculty and systems engineering students applied a systems analysis to characterize cross-domain multi-mission situations and develop system concepts for AI-enabled mission planning and tactical decision-aids for multi-mission resource allocation and dynamic replanning. The team conducted a needs analysis, requirements analysis, and conceptual design using model-based systems engineering tools to capture system and architectural design artifacts. The students developed names for the automated systems: the Strategic Operational Decision Aid for the automated system that could support future mission planning (Lee, 2022), and the Multi-Mission Resource Allocation system for future tactical-level automated decision support (Ghigliotti et al., 2022).

The NPS research team studied the operational need for automated planning and decision aids for cross-domain multi-mission situations that arise during military operations. The team drew upon former research that the PI performed that characterized instances of complexity in military operations that result in situations that require automated decision support systems. Highly complex tactical military decision spaces can be characterized as having extremely short reaction or decision timelines, significant levels of uncertainty in situation awareness knowledge, extreme dynamics in the threat tempo in terms of heterogeneity, number, and kinematics, and information confusion with too little or too much information. These complex situations can cross military domains and involve operations in space, air, land, sea, undersea, and cyber. These complex situations can also involve concurrent multiple missions, such as anti-surface warfare, air and missile defense, undersea warfare, mine warfare, strike operations, cyber operations, operations in communication denied environments, expeditionary missions, etc. When warfare resources are needed for concurrent multiple missions, the decision space for resource allocation becomes complex. This complexity increases in cross-domain situations. Automated decision aids leveraging AI and advanced analytics is a candidate for improving (and even enabling) effective mission planning and tactical decision-making in these situations.

The study topic sponsor can use the findings of this research project as a basis for funding the research and development of advanced analytics capabilities for multi-mission cross-domain mission planning and tactical decision aids. One step is to continue studying AI and advanced data analytic methods as a means of automating mission planning and tactical decision-making. Another step is to continue studying operational scenarios that involve concurrent multi-mission cross domain operations. The topic sponsor can use the foundational knowledge from this study to continue to pursue these critical capabilities for the Navy.

Recommendations for Further Research

The Naval Postgraduate School study team recommends that automated methods including advanced data analytics and artificial intelligence (AI) be pursued for mission planning and tactical decision aids that can improve cross-domain multi-mission resource allocation and dynamic replanning. The team recommends further study into (1) the characterization of complex tactical situations where cross-domain multi-mission operations are required; (2) the need for mission planning, dynamic replanning, and tactical decision-making that can address these complex situations; and (3) concepts for leveraging advanced data analytics to provide automated planning and decision aids for these applications. The team recommends the following specific research initiatives as future work:

- Operational concept studies—to understand how/when complex military operational situations arise that involve cross-domain and concurrent multi-mission solutions
- Development of modeling and simulation capabilities to support more detailed study into these complex operational situations and potential solutions
- Continued research into advanced AI and data analytic methods

- Study into system architectures that can enable dynamic replanning to occur during tactical operations

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NPS-22-N336-A: Robustness and Vulnerability Measures of Deep Learning Methods for Cyber Defense

Researcher(s): Thor Martinsen, and Wei Kang

Student Participation: ENS Elana Kozak USN, and ENS Philip Smith USN

Project Summary

Navy networks and infrastructure are under frequent cyberattack. One developing area of application for machine learning (ML) is cybersecurity. However, the susceptibility of ML to adversarial data is an important issue that must be studied and addressed before these systems can safely be incorporated into US Navy systems and operations. The robustness of deep learning (DL) techniques used in computer vision and language processing have been extensively studied. Less is, however, currently known about the vulnerabilities and robustness of DL methods suitable in cybersecurity applications. The goal of this study is to investigate mathematical concepts of robustness and vulnerability of ML systems that are subjected to data poisoning attacks. The first phase of the project includes a thorough literature review. The second phase of research focuses on robustness analysis of infrastructure cybersecurity. Using a microgrid power system model and learning-based fault detection as our testbed, we investigate the robustness of neural networks subjected to noisy or poisoned data. In the third and final phase of the project, we explore distributional robustness of neural networks. The findings and conclusions from our study include the following: The concept of robustness is not uniquely defined in the existing body of adversarial machine learning research literature. When incorporating ML technology into US Navy systems, it is important that deep neural networks (DNN) be purpose-built and that they are trained with a slightly higher level of noise than what is expected in their normal operating environments. Whenever possible, we also recommend incorporating ML-redundancy and simultaneously operating several DNNs with different network topologies. Research indicates that although they may perform similarly under normal

conditions, their performance can differ in the presence of noise. Such disparities can be used to detect the presence of noise and inform operators that a data poisoning attack may be taking place.

Keywords: *machine learning, deep learning, adversarial machine learning, data poisoning, robustness, cybersecurity, infrastructure security, fault detection*

Background

Sophisticated cyber actors and nation-states are developing capabilities to disrupt, destroy, or threaten the delivery of essential services. According to the Cybersecurity & Infrastructure Security Agency (n.d.) "As information technology becomes increasingly integrated with physical infrastructure operations, there is increased risk for wide scale or high-consequence events that could cause harm or disrupt services upon which our economy and the daily lives of millions of Americans depend." Many of the United States Navy's operations depend upon physical infrastructure such as the power grid and computer networks. These days, cybersecurity plays an essential role in protecting a wide spectrum of critical systems and infrastructures. This research will provide the Navy Cyber Defense Operations Command with information regarding potential vulnerabilities of DL systems as well as propose some computational methods to aid the command with determining the robustness of DL embedded systems should they be employed in future Navy networks.

The use of AI and ML in cybersecurity settings is an area that is attracting increased attention. For instance, supervised learning is studied by researchers to classify particular security problems such as denial-of-service attacks or to identify different classes of network attacks such as scanning and spoofing. There have been many approaches to network intrusion detection using DL such as deep belief networks and restricted Boltzmann machines. Deep belief networks can also be applied to detect malware attacks. Studies show that the combination of feature selection and deep neural networks is capable of performing malware classification tasks. The stacked auto-encoder, a special kind of DNN, can be used for network traffic identification and protocol classification. Despite promising results from existing DL research, neural nets have been shown to be susceptible to adversarial data poisoning (i.e., small perturbations of input data designed to cause output variations that lead to errors such as mislabeling or misclassification). The robustness of DL techniques used in computer vision and language processing have been extensively studied. However, less is currently known about the vulnerabilities and robustness of DL methods suitable in cybersecurity applications. The problem of quantitatively measuring the robustness and vulnerability of DL for cybersecurity applications is the focal area of this project.

The first phase of the project includes a thorough literature review. The second phase of research focuses on robustness analysis of infrastructure cybersecurity. Using a microgrid power system model and learning-based fault detection as our testbed, we investigate the robustness of neural networks subjected to noisy or poisoned data. In the third and final phase of the project, we explore distributional robustness of neural networks.

Findings and Conclusions

Our research shows that the concept of robustness is not uniquely defined in the existing body of ML research literature. There are a variety of different aspects of robustness that may affect the performance of an ML model. The study and evaluation of robustness should, therefore, be tailored with the specific application in mind. Most machine learning robustness studies have thus far focused on traditional machine learning applications such as computer vision, image classification, and language processing. However, some techniques found in the existing literature are applicable to a wider spectrum of application scenarios.

This study focused on robustness analysis of infrastructure cyber security. Using a microgrid power system model and learning-based fault detection as the testbed, we investigated the robustness of DNNs under noisy or adversarial data. From the study, we conclude that noise drawn from a variety of different distributions with the same mean and standard deviation produce the same or very similar results when it comes to the DNN's ability to detect faults. However, adding adversarial noise in the direction of the network gradient produced substantially different effects from that of random noise distributions. In addition, computation shows that more complex networks do not necessarily result in more robust networks. During the project, we added uniform random noise to the training data. Subsequent testing showed that the lowest error rates were achieved when a network was trained with slightly higher noise levels than those present in the testing data. This finding is important in real-world applications where noise is expected in the input data. In such cases, the ML model should be trained with additional noise added to the training data set.

Distributional robustness was also investigated. DNNs may sometimes be used outside of the environment in which they were trained. If the input data's distribution is significantly different from that of the training data, it could negatively impact the performance of the network. The dynamic behavior of the input data is critical to distributional robustness of the system. For dynamical systems, the initial distributions for trajectories of the system can be vastly different. However, the dynamic nature causes the data points along trajectories to converge to a similar pattern, regardless of the initial state distributions.

The findings in this study are intended to inform the technical staff and leadership at the Navy Cyber Defense Operations Command. When incorporating ML technology into Navy Networks and Defenses, we recommend ensuring the DNNs in question are purpose-built for the intended application and are trained with a slightly higher level of noise than what is normally found in the testing data. Whenever possible, we also recommend that ML-redundancy be built into the system. Although DNNs with different network topologies may perform similarly under normal conditions, our research indicates that their performance can differ in the presence of noise. This disparity can be leveraged to detect the presence of noise in the system and inform operators of aberrant operational conditions or the potential of a data poisoning attack is taking place.

Recommendations for Further Research

One of the conclusions of this research project is that the evaluation of machine learning (ML) robustness should be tailored with the specific application in mind. Future study of ML robustness in support of the Navy Cyber Defense Operations Command should focus on applying the testing methods developed in this project to real-world Navy network data. This includes selecting specific machine learning tools to evaluate, collect, and format real-world network data, and conducting off-line computations and simulations to find the effects of added random noise and adversarial perturbations. If possible, we recommend incorporating and testing several neural networks with different network topologies that simultaneously process incoming data. Results from our study indicate that performance and predictions disparities among different neural networks could potentially be used to indicate the presence of noise or that adversarial attacks are occurring within a network. Finally, our research also indicates that the dynamic behavior of data can be critical to the overall robustness of a system. Identifying and studying the dynamic nature of data resident within operational US Navy networks should consequently be considered when carrying out future ML robustness research.

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N3/N5 - Plans & Strategy

NPS-22-N052-A: Nuclear Deterrence and the Space and Cyber domains.

Researcher(s): Matthew Crook, Wenschel Lan, and James Newman

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Project Summary

The space and cyber domains are newer than the traditional warfare domains, behavioral norms between nations are not well-defined and intentions can be easily misunderstood. Additionally, situational awareness in these new domains is not well developed, which may allow potential adversaries to operate covertly, with less risk of their actions being attributed to them. This situation can destabilize nuclear deterrence efforts. This project draws on the expertise of many students at the Naval Postgraduate School in the Space Nuclear Command, Control, and Communications (NC3) four-course certificate program. These students have considered the problem and presented their findings and conclusions. The students worked independently, and some of their conclusions were similar.

Students agreed that there were few actions in the cyber domain that would justify a nuclear response, so long as positive control of the US nuclear weapons could be maintained. To this end, an analysis of the US NC3 thinline should be conducted to verify no vulnerabilities exist from a cyber threat vector. NC3 thinline architecture should be independent of cyber domain interconnections to the maximum extent possible.

US NC3 Space Systems that support the thinline as a primary mission should also be disconnected from the cyber domain as much as possible, including the command and control of these spacecraft. This is especially difficult, since these spacecraft have dual non-nuclear missions which may rely on these connections.

Geostationary spacecraft are also no longer safe from kinetic attack in a major conflict and they are few in number. It may be worth exploring a constellation of highly proliferated low earth orbiting satellites like several commercial companies are currently building. Such a highly proliferated satellite constellation would be more difficult to disrupt with kinetic weapons due to the large number of spacecraft present in highly proliferated satellite constellations.

Keywords: *nuclear command control and communications, NC3, nuclear command and control, NC2, cross-domain, nuclear deterrence, cyber domain, space domain*

Background

The space and cyber warfighting domains are newer than the traditional domains of air, land, and sea. International stability in the traditional warfighting domains benefits from decades to centuries of events that have led to commonly understood and internationally accepted behavior, policies, treaties, and robust situational awareness that help enforce treaties and agreements. However, behavioral norms between governments in these new domains of space and even more so the cyber domain, are not well established. Additionally, situational awareness in the space and cyber domains is far less developed than in the traditional domains, and this can allow aggressors to act with less risk of detection or attribution. The fog of war is thick in the space and cyber domains, as it once was in the traditional domains, which can make international agreements difficult to enforce. The lack of situational awareness combined with the lack of behavioral norms in the space and cyber domains can be destabilizing and leave large room for misunderstanding and miscalculation on both sides of a potential conflict.

This is especially concerning when considering the mission of nuclear deterrence. It's generally agreed that for nuclear deterrence to be credible and effective, each nation requires high situational awareness, transparent attribution, strong behavioral norms and agreements between nations, and a clear understanding of the adversaries' intentions. In the past, nuclear redlines between the USA and USSR/Russia have helped clarify actions that could lead to nuclear escalation.

This research seeks to shed light on the following questions, and provide policy recommendations to add stability in the future, and to help the US maintain a credible nuclear deterrent.

1. Is US deterrence effective in deterring attacks against the Nuclear Command and Control (NC2) systems via space and cyber vectors?

2. What actions in the space or cyber domains would result in an event significant enough to warrant a US kinetic response, and could these actions include crossing the nuclear threshold?

3. How can aggression be measured across domains that influence nuclear deterrence and escalation management?

4. What strategies exist to manage escalation and improve deterrence?

5. What is the nuclear threshold in the space and cyber domains, if any?

NPS students enrolled in the NC3 certificate program participated in this study. Each student was assigned a final paper as part of their class work on this topic that was to be at least 3000 words in length or longer. In addition to the student findings, the principal investigator also researched answers to these questions by lead academics, government agencies, and other knowledgeable sources. The findings are described in detail in the Technical Report.

Findings and Conclusions

International law, policies, and established norms in other domains such as sea, land, and air add stability, and understanding, and provide clarity to potential adversaries' intentions in those domains, which reduces the likelihood of armed conflict due to misunderstanding or miscalculation. However, in the space and especially the cyber domains, international law, policies, and norms are not well established, which leads to destabilizing effects from misunderstanding of adversaries' intentions, and miscalculation. Additionally, potential adversaries may view agreements as unenforceable if they do not believe that their actions can be observed or attributed to them, and may lead them to take escalatory actions that they wouldn't dare take otherwise.

Usually, actions in the cyber and space domains by an aggressor intending to gain advantage over a victim must be done covertly. If the victim at any point becomes aware of the intrusion or vulnerability being exploited, the victim can usually protect itself by patching the vulnerability with more ease than it took for the aggressor to gain access, and the aggressor will have lost the advantage it once enjoyed.

Unilaterally, or with NATO and other allies, the US should endeavor to add systems that will provide situational awareness and visibility in these novel domains, to reduce the temptation by potential adversaries to take actions that they would not take if they knew their actions could be observed and attributed to them. US Cyber Command should make situational awareness in the cyber domain a top priority, while the US Space Command should do the same in the space domain. Adding situational awareness will take years and decades but should provide additional stability and transparency as it is achieved.

The US State Department, with specific recommendations from the Department of Defense (US Cyber Command, US Space Command, US Strategic Command, and other appropriate entities), should peruse international agreements to define norms in the space and cyber domains conducted by national militaries, especially actions that could undermine nuclear deterrence, the credibility of nuclear systems, and any systems used for NC2.

Establishing nuclear redlines in the cyber domain without adequate situational awareness may not be as effective as in other domains. The relevant uniformed services (US Space Force, US Air Force, and US Navy) should, under the guidance of the proper combatant commands (US Cyber Command, US Space Command and US Strategic Command), endeavor to reduce or eliminate NC2 cyber domain dependencies from the NC3 thinline. The goal would be to reduce, to the maximum extent possible, threats from the cyber domain on US nuclear systems, and nuclear credibility.

Recommendations for Further Research

The US Cyber Command should lead the research effort and investigate tools and strategies to gain additional situational awareness in the cyber domain. This should be an ongoing long-term effort requiring highly skilled cyber experts with precise knowledge of US classified systems in the Department of Defense (DoD) and elsewhere. The long-term goal is to gain enough situational awareness of US Government-owned systems such that potential adversaries cannot operate in the cyber domain with impunity, but rather must assume that their actions can be observed if their actions touch US DoD or US Government systems, especially those of US Nuclear Command and Control (NC2). The architectural changes needed to implement such situational awareness may be vast and require decades of updates to US Government systems. These changes should not unlawfully or unnecessarily encroach on US citizens' privacy, but rather apply to US Government systems only. However, recommendations and requirements could be provided to US companies and US DoD contractors to help protect against state-sponsored corporate espionage.

Similar to the recommendations for the US Cyber Command above, the US Space Command should lead the effort to research and investigate tools and strategies to gain additional situational awareness in the space domain, as well as techniques for space control. This should be an ongoing long-term effort requiring highly skilled space systems experts with an awareness of specific US capabilities.

The US Strategic Command should lead the research effort into disaggregated mesh networked NC thinline architectures. In theory a mesh network could continue to operate even if multiple nodes were disrupted or destroyed. A network with a much larger variety of links between nodes may be more robust, provide more redundancy, and may make it more difficult for an adversary to disrupt without revealing their identity.

Since geostationary spacecraft are few in number, and no longer safe from kinetic attack, it may be worth a shift in US Nuclear Command, Control, and Communications (NC3) thinline space architecture to a highly proliferated low earth orbit satellite constellation. Such a system may be more redundant, resilient, and more difficult to disrupt, and such a constellation would not necessarily cost more than a highly protected geostationary constellation, since each spacecraft would be smaller, less expensive, and many could be placed in orbit per space launch. Many commercial companies have already pioneered the development of technology needed to facilitate such systems, and this technology could be leveraged.

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NPS-22-N053-A: Implications of Two Peer Nuclear-Armed Adversaries on U.S. Deterrence Strategy and the Future of Arms Control Agreements

Researcher(s): Aleksandar Matovski, Jeffrey Larsen, Christopher Twomey, and Mikhail Tsypkin

Student Participation: No students participated in this research project.

Project Summary

Tracks 1 and 2 of this research challenge the conventional wisdom that Moscow's shift toward Beijing was mainly the result of geopolitical ambitions and external threats from the West. Instead, this study highlights regime (in)security as a primary driver of the Kremlin's behavior. The analysis finds that the crucial breakthroughs in this relationship have occurred not as a reaction to perceived Western encroachment, but in the wake of major protest waves that have threatened the Putin regime's grip on power domestically. Responding to these challenges, the Kremlin has subordinated Russia's foreign and security policy to the interests of regime survival, adopting a confrontational posture toward the West to rally nationalist sentiments, demobilize opposition, and justify its growing authoritarianism. This study's empirical analysis shows that Moscow has pursued partnership with Beijing, often in defiance of geopolitical logic and Russia's broader interests, to mitigate the costs of this assertive international stance.

The purpose of Track 3 of this research is to provide insight into the North Atlantic Treaty Organization's (NATO) adaptive responses to Russian behavior in the past year. Based on an extensive review of the literature and field research in Europe that included interviews with security experts at NATO Headquarters, US Air Forces in Europe Headquarters, the European Union, the German Ministry of Defense, and think tanks, the study finds that Russia's blatant violation of what many had assumed to be a new reality of peace in Europe has made NATO much more cohesive, and convinced some member states who were leaning toward Moscow that that their real security lies with NATO. The Track 3 study also

examines the implications of NATO's new Strategic Concept, which for the first time specifically mentioned China as a future threat to European security and prosperity.

Keywords: *Russia, China, strategic alignment, omnibalancing, trilateral strategic competition*, *North Atlantic Treaty Organization, NATO, deterrence, nuclear weapons, United States, Germany, Great Britain, arms control, security, defense, Cold War, Eastern flank, Ukraine, strategic concept, NATO-Russia Founding Act, strategy, European Union, Sweden, Finland, F-35 aircraft, dual-capable aircraft*

Background

The main objective of the Track 1 and 2 of this research is to reexamine the basic assumptions about the nature of the rising strategic alignment between Russia and China, and to address some of the key gaps in the current understanding of the relationship between these two U.S. adversaries. This study proposes a new framework for interpreting the Sino-Russian strategic alignment, which showcases the concerns about regime survival of the Russian and Chinese autocracies as the main drivers of their rapprochement. The analysis shows that Moscow and Beijing became increasingly antagonistic toward the West and converged with each other in the wake of major protest waves that threatened their grip on power domestically. In particular, the weakening Putin regime has sought confrontation with Russia's neighbors and the West to create a sense of external threat that would justify its authoritarian rule and demobilize the growing domestic opposition.

Against this backdrop, a highly lopsided pact with Beijing has been the only way for the Kremlin to sustain its hyper-confrontational authoritarian survival strategy. Desperate for Chinese help to survive isolation and sustain its aggressive posture toward the West, the Putin regime has been the primary catalyst of the Sino-Russian partnership. Seeking Chinese diplomatic support and an economic lifeline to help weather Western sanctions, the Kremlin under Vladimir Putin's leadership dismissed long-standing concerns about Chinese encroachment, and seems poised to offer unprecedented geopolitical concessions, which can benefit China immensely.

The Track 3 of this research is set against the backdrop of unprecedented challenges posed by Russia, which have resulted in a strong, cohesive response by the allies, including closer transatlantic cooperation, a significant increase in U.S. troops and equipment deployed to Europe, and similar increases in European national commitments to buttressing the new eastern flank. Two long-standing neutral states—Finland and Sweden—have requested membership in NATO, the Alliance has quadrupled its forces along the borders of Russia and Belarus, Germany has made surprising and significant changes to its security policies and defense spending, Great Britain has developed a strategy to once again become a global power, and Western sanctions are crippling the Russian economy. All of these represent a major change in the geopolitical situation in Europe, which may lead to a weaker, but even more desperate and dangerous Russia, thus requiring NATO to remain strong and vigilant. In addition, the Alliance now recognizes China as a future competitor and potential adversary.

Findings and Conclusions

The core study of Tracks 1 and 2 of the research finds that Russia and China's convergence has been primarily driven by the domestic security concerns of these autocracies. In particular, the Kremlin has pursued a confrontational strategy with the West, aimed to justify authoritarianism as a response to external threats. As this has overstretched Russia's declining power, the Russian leadership has committed to an unfavorable partnership with Beijing to offset the costs of this excessively confrontational posture. These dynamics have profound implications for deterrence, according to the findings of this study. Critically dependent on Chinese support for its survival, the Putin regime cannot be placated or induced to split with Beijing with geopolitical concessions like limiting NATO enlargement, neutrality for Ukraine, or sanctions relief. Moreover, the Kremlin is willing to make unprecedented concessions for Chinese support, granting Beijing access to Russia's resources and strategic regions like Central Asia. Against this backdrop, Beijing has little incentive to deny Russia the economic lifeline as a collapse of the Putin regime could pose a major geopolitical risk and undermine China's dictatorship.

The study in Track 3 of this research finds that Russia's aggression in Ukraine has made the NATO member states more cohesive and willing to stand up to Russia than they have been in decades. In turn, the overlapping membership with NATO has made the commitment by the European Union to stand up to Russia equally compelling, leading the Union to impose and maintain extensive economic sanctions on Russia. The study finds that this new context has led to a significant change in NATO's posture. Acknowledging the worsening global security situation, NATO has adopted a new strategic concept that for the first time, mentions China as a future threat. The Alliance has also approved a new military strategy for the first time in 55 years, replacing the strategy of flexible response.

Recommendations for Further Research

Based on the results of the study in Track 1 and 2 of this research, four broad recommendations for further research can be made. The first is to analyze how conduct of the war in Ukraine and the internal political situation in Russia may affect its stance on its strategic partnership with China —particularly whether Russian sensitivities to becoming a "vassal state" to China could constrain their cooperation. Conversely, it should be investigated whether a closer Sino-Russian alignment in this new geopolitical environment emboldens or restrains Russian aggression in Ukraine and beyond—particularly in terms of the employment of nuclear weapons. The second recommendation based on this study is to examine the extent to which the Russian defense industry—particularly the industrial base for its strategic forces and space capabilities—can compensate for the negative effects of Western sanctions through the import of critical components and technologies and other support from China. Finally, the study implications suggest a need to reassess the strategies for containing Russia's aggressive behavior and motives to cooperate with China in the wake of the 2022 invasion of Ukraine.

The findings of the Track 3 study indicate that the sponsor agency would benefit from continued research into the European security environment, especially examining how Russia's foreign policy and military moves affect US allies in the region. This will be valuable for N5 in determining how to best provide extended deterrence guarantees to US allies, while at the same time dealing with a rising threat from China in the Indo-Pacific region. Such a three-player relationship will be quite challenging to understand. It will require considerable analysis to determine the appropriate deterrence approach to each potential adversary. Those considerations will require tailored deterrence, and that requires in-depth knowledge of each adversary, their goals, their approaches, and the points at which the US might be able to provide some leverage or pressure to ensure deterrence remains operable and effective. Similarly, one must understand our allies in order to know what assures them of continued US extended deterrence guarantees, and whether those perspectives are changing as a result of adversary behavior in their region. This implies a need for regional studies by experts in the fields of both nuclear deterrence strategy and area studies.

References
None

NPS-22-N053-B: Nuclear Deterrence and Arms Control Agreements between three Peer Adversaries.

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Student Participation: CPT Kyle Santarelli USA, Maj Isaac Williams USMC, Capt Steven Bourdow USMC, LT Levi Rosa USN, and LCDR Bryan Lay USN

Project Summary
China has emerged as a peer military and economic adversary to the United States and Russia. This changes the balance of power and dynamics of nuclear deterrence, which has traditionally been based on a bilateral contest between the old cold-war nuclear-armed superpowers. In some cases, adjustments to U.S. policy, agreements, and nuclear deterrence strategy may be warranted.

This project draws on the expertise of many students at the Naval Postgraduate School in the Space Nuclear Command, Control, and Communications four-course certificate program. The students in this certificate program have experience in nuclear deterrence as their military operational specialty. The students were required to write a final paper for the class considering the research questions posed and use minimum of sixteen credible references to support their findings. These students have considered the problem, conducted analysis, and synthesized the works they referenced and presented their findings. They worked independently, and some of their conclusions were similar.

The U.S. and China are peers militarily and economically, while Russia lags in these areas. However, Russia is the only nuclear peer to the U.S., while China lags. China's nuclear arsenal has been smaller for decades due to a policy of minimum deterrence; however, it seems a shift is occurring in this strategy as China increases its nuclear forces.

Students generally agreed that arms control agreements that included the U.S. and Russia, but not China, would come under strain as China would be free to pursue weapons and other nuclear systems prohibited by the agreement between the other two. Although China has rebuffed past efforts to participate in arms control agreements, the U.S. should continue to seek agreements and attempt to convince Beijing of the security and stability nuclear arms control agreements could bring.

Keywords: *nuclear command control and communications, NC3, nuclear command and control, NC2, nuclear deterrence, China, Russia*

Background

Classical nuclear deterrence strategy was based mainly on the existence of two nuclear-armed peer adversaries. However, China has emerged as a third nuclear superpower. China is already a peer economically and militarily. While its nuclear arsenal is substantially smaller than that of the U.S. or Russia, it is actively expanding and increasing its nuclear capabilities. There have never existed three nuclear-armed superpowers, and these may upend assumptions on which previous nuclear deterrence strategy was built. At a minimum, the U.S. should reevaluate nuclear deterrence in light of this new reality to determine if changes should be made to U.S. nuclear deterrence strategy and policy.

While China and Russia have no formal alliance, Sino-Russian relations are generally agreed to be on friendlier terms than they have been since the 1950s, and they have agreed informally to build an alliance against the U.S. (Trofimov, 2019).

This research seeks to shed light on the following questions and provide policy recommendations to add future stability and help the U.S. maintain a credible nuclear deterrent.

The research questions considered were:

1. How does the dynamics of nuclear deterrence change when there are three peer nuclear adversaries?
2. How might the new peer adversary's behavior change as they move status within the nuclear deterrence framework?
3. How might the current peer adversary behavior change as a third peer actor change the deterrence framework?

Students in the Space Nuclear Command, Control, and Communications certificate at the Naval Postgraduate School studied this problem, considered these questions, and presented their findings in the technical report. Students analyzed the problem from personal experience and various resources available and referenced them in their final papers.

Findings and Conclusions

The U.S. and Russia maintain nuclear arsenals about 20 times larger than China's, but China is increasing the size of its nuclear arsenal. China summarily rejected the Trump administration's efforts to include China in the New Start Treaty in 2019 and released a statement stating that the U.S. and Russia must first reduce their own numbers of nuclear weapons before participating in multi-lateral nuclear arms agreements.

The New Start Treaty is currently the only nuclear arms control agreement between Russia and the U.S.. This treaty also provides on-site inspections, required notifications between countries, bilateral meetings, and data exchanges, which generally offer robust compliance verification. Meanwhile, China has begun expanding its nuclear arsenal, and it is expected to reach 700 warheads by 2027 and 1000 warheads by 2030 (Bugos, 2021).

Ideally, the U.S. and Russia would continue to make arms control progress and further reduce arms bilaterally. This is a challenge due to Russia's unprovoked invasion of Ukraine, threats to use its nuclear weapons, and Vladimir Putin's general unwillingness to continue to reduce nuclear weapons (even before the war). The outcome for Ukraine, Russia, and the world due to this war is uncertain, but the U.S. should remain ready to engage with Russia (and China) at any time. Further reduction in nuclear arms bilaterally with Russia may not be feasible in the short term. Still, the U.S. should remain ready to continue reducing nuclear arms along with Russia as soon as Russia is again amiable to such a course of action.

The U.S. seems to have few options to pressure China or offer incentives to keep the number of nuclear arms small relative to the U.S. and Russia. At first glance, it may seem hypocritical for the U.S. to ask this of China, while the number of weapons in the U.S. arsenal is much larger. However, diplomatic or economic incentives might still persuade China. The U.S. has not declared a policy of "no first use"; however, it could take this policy but only towards nations with a nuclear arsenal much smaller than the U.S., such as 25% or fewer warheads. Additionally, if China acquires a much larger nuclear arsenal, it might become more difficult to persuade Russia to reduce the size of its arsenal. Therefore, the U.S. should work to find common ground with China (in nuclear deterrence) with open dialogue and find methods to mutually pressure Moscow to reduce the size of its nuclear weapons cache. It should be clear to China that the U.S. is wholly interested in reducing the role of nuclear weapons.

Recommendations may need to be adjusted based on the world situation in the near future. Nonetheless, there is potential to spiral into the next nuclear arms race. The U.S. must continue pursuing nuclear stability with Russia and China through regular dialogue. The U.S. should continue to understand China's nuclear ambitions and what motivates its leadership to expand its arsenal now while it has remained small for many decades.

Recommendations for Further Research

Future research should aim to understand how the Chinese leadership perceives nuclear deterrence and how they view the U.S. nuclear posture. This should include finding common ground with China in realm of nuclear deterrence and, if possible, investigate how it might be possible to present a united front and place pressure on Russia to further reduce the number of nuclear weapons in its arsenal.

The U.S. Naval War College (USNWC) Wargaming Department already conducts an annual nuclear deterrence wargame on behalf of the US Strategic Command (USSTRATCOM). USSTRATCOM or other appropriate government agencies should commission a wargame or series of wargames to consider the problems of three peer nuclear-armed adversaries, emphasizing the most effective strategies to deter the use of nuclear weapons and deter expanding nuclear arsenals. The USNWC may be the most experienced in strategic nuclear deterrence wargames at a classified level.

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NPS-22-N055-A: Strategic Deterrence and Nuclear Weapons Influence on Taiwan Contingency Operations

Researcher(s): Jeffrey Appleget, Lyla Englehorn, Christopher Twomey, Marianna Jones, and Robert Burks

Student Participation: LT Luke Goorsky USN, MAJ William Brown USA, LT John Allen USN, and LT Andrew Dicksey USN

Project Summary

A team of four NPS students designed, developed, conducted, and analyzed a wargame to generate the findings for this project. The wargame was designed and developed from March to May of 2022 and then conducted and analyzed in June 2022.

The wargame investigated three key issues:

1. What are the most effective (of likely) levers of power for deterrence that would affect DOD operational level tasks in a Taiwan Strait scenario?
2. How does the United States (U.S.)/People's Republic of China (PRC) measure intent and objectives?
3. How does the U.S./PRC signal intent, objectives, and red lines?

These issues were examined in the following 2025 scenario:

Civil unrest is rising throughout China's semi-autonomous states. In response, China sends armed police to stabilize the situation. As China uses aggressive tactics to quell civil unrest, Taiwan reaffirms its status as an independent country. In response to this declaration, China begins to mobilize forces in preparation for a military exercise that will encompass all the littorals of Taiwan. The Chinese military exercise will be the largest to date, and Taiwan assesses that Chinese forces may transition from military exercises to military operations. Taiwan's armed forces take defensive positions for force protection and contingency operations.

The insights in response to the three questions were carefully analyzed from wargaming output and were compiled, briefed, and reported to the sponsor. Because of the sensitivity of these results, they are controlled unclassified information. The insights were provided to the sponsor via the Controlled Unclassified Information (CUI) Wargaming Executive Summary submitted to the sponsor in June 2022. Additionally, a paper authored by Dr. Chris Twomey was provided to the sponsor o/a 22 October 2022.

Keywords: *strategic deterrence, nuclear weapons, People's Republic of China, Taiwan, contingency operations, Taiwan Straits*

Background

Study Purpose: The sponsor requires a deeper understanding of strategic actions and counteractions that could occur between the U.S. and the PRC as capabilities of each side change over time so that the U.S. can anticipate and plan for changes and/or augmentation to U.S. strategic deterrence policy in the Western Pacific. As the U.S. and PRC edge closer to parity in military capability, both sides must be acutely aware of how these changes can increase the chance of conflict breaking out. The U.S. must maintain an effective deterrent against the PRC in the Strait. At the same time, China must ensure that its rapid military rise does not force the U.S. to act against it before PRC military capabilities outpace U.S. military capabilities. This game aims to capture lessons learned from the outbreak of conflict in the Taiwan Straits to further the deterrence relationship between the U.S., Taiwan, and PRC.

Methodology: This study was conducted using a wargame. This wargame was a seminar-based hybrid system with separate timed planning, decision, and adjudication phases. The system limits decisions in time, space, and force applications. The game consisted of sequential turn-based actions and reactions in a seminar format with a white cell enforcing guidelines based upon items such as doctrine, national-level intent, and international reactions.

Wargame Execution: In-game turns represented one-week time blocks. Units manipulated by players were at the operational level of war.

Turn Steps:

i. **Signal planning—**Each side gets 15 minutes or fewer to internally discuss their moves for the turn.
ii. **Signaling—**5-minute phase where actions by both teams are in the open and displayed to the other side in real time. Each team places their signal tokens and draws action cards. Signal tokens can be moved, and action cards can be picked up or discarded during these 5 minutes.
iii. **Operations Planning and Orders Writing—**Each side uses their action cards and provides orders to their units. Orders include unit, type of action, and desired end state of the action.
iv. **Operations Execution—**White Cell receives orders from each side and adjudicates results.
v. **Adjudication and Feedback—**Any dice rolls are conducted by each time, and interviews are conducted with players to garner insights into strategies and anticipated enemy responses.

Player Actions:

i. **Prepare:** Move forces out of garrison, get ships underway, ready nuclear forces
ii. **Move:** Deploy a naval task force into a theater, forward deploy ground units
iii. **Operate:** Conduct long-range aviation missions, conduct strikes against enemy forces, conduct combat air patrols

Order of Play: All phases of the wargame were conducted simultaneously with signaling and overt force placement conducted on a common, virtual gameboard. Covert force movements, such as Special Operations Forces deployments and underway submarines, were conducted on the respective team's physical gameboard.

Adjudication: End-of-turn adjudications included items such as resolving potential combat engagements, resolving movement intentions, and effectiveness of non-kinetic operations.

Data Collection: Data collected included orders written at the beginning of the turn, player actions, and the results of adjudication.

Findings and Conclusions

These are the three key issues that findings and conclusions were developed for:

1. **Key Issue 1:** What are the most effective (of likely) levers of power for deterrence that would affect DOD operational level tasks in a Taiwan Strait scenario?
2. **Key Issue 2:** How does the U.S./PRC measure intent and objectives?
3. **Key Issue 3:** How does the US/PRC signal intent, objectives, and red lines?

The insights in response to the three questions were carefully analyzed from wargaming output and were compiled, briefed, and reported to the sponsor. Because of the sensitivity of these results, they are controlled unclassified information. The insights were provided to the sponsor via the CUI Wargaming Executive Summary submitted to the sponsor in June 2022.

Limitations of the study include the following:

i. **Personnel—**Game volunteers were difficult to locate due to the game's execution during the final week of NPS classes and the week before NPS finals. Continuity was lost, with only three of the original nine volunteers being present for the entirety of the game.
ii. **Classification—**Keeping the game at the controlled unclassified information level was a barrier to realism, particularly when considering submarine operations and cyber effects.
iii. **Experience—**The game players lacked broad experience and often focused on their specific warfare area of expertise to achieve their objectives.

The findings both confirmed original expectations and presented areas for future research. The sponsor will take the study's results and use them to inform a path forward for future research.

Recommendations for Further Research

We recommend future wargames and similar analytic events be conducted. We recommend workshops to better understand the People's Republic of China's (PRC) capabilities and their potential actions and reactions by leveraging PRC cultural experts as necessary events to set the stage for more detailed wargaming.

Future wargames may include the following:

1. Conducting the same wargame with players who have more appropriate backgrounds and expertise.
2. Conducting the same wargame at higher levels of classification.
3. Expanding the wargame to incorporate new and emerging knowledge of PRC capabilities.

Because this is such a relevant topic whose findings should drive U.S./PRC policies, we recommend that there be an annual recurring wargame that continues to examine these issues in order to inform new policy and doctrinal choices for the U.S. Department of Defense.

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NPS-22-N094-A: Leveraging Naval Diplomacy to Reinforce Economic Programs and Compete with China

Researcher(s): Emily Meierding, Rachel Sigman, and Christopher Darnton

Student Participation: No students participated in this research project.

Project Summary
To counter rising Chinese influence, the United States Navy (USN) must plan and implement its overseas operations and diplomatic activities to maintain and strengthen U.S. alliances and partnerships. This study's core question is, "How can the USN leverage its operations and activities to reinforce U.S. economic programs and enhance U.S. influence?" Using fieldwork, interviews, and desk research, the research team examined USN activities, U.S. economic programs, and host government security interests in "indicator" countries in their respective regions: Chile in Latin America and the United Arab Emirates (UAE) in the Middle East. The project's core finding, which has not been emphasized by previous research, is that the standard U.S. understanding of building capabilities and relationships, based on conventional assets for warfighting and deterrence within a robust alliance like NATO, frequently does not match partner nation security priorities outside of that context. In countries such as Chile and the UAE, where the operative concepts are economic development, international prestige and autonomy, and internal stability, platform sales and training are insufficient for building enduring, influential alliances and partnerships. The study recommends that U.S. security cooperation efforts more creatively consider how to feed into partner nations' highest-priority issues, such as technology transfer and regional leadership roles and recognition. It notes that this type of engagement will require careful grappling with unique local political contexts and challenges, and consideration of how these intersect with U.S. government policy priorities, American values, and nonmilitary lines of effort, especially when these touch on sensitive questions of internal stability and domestic security.

Keywords: *naval diplomacy, maritime security cooperation, economic cooperation, allies, partners, influence, great power competition, strategic competition, capacity-building, foreign military sales, training,*

naval operations, prestige, reputation, China, Belt and Road Initiative, BRI, Chile, United Arab Emirates, UAE

Background

Over the last fifteen years, China has been extending its global engagement through economic activities, including the Belt and Road Initiative (BRI), and increasing security cooperation with partner states. China's growing global presence has prompted concerns that the United States' relative power and influence could diminish, leading U.S. policy makers to reorient towards strategic competition (White House, 2017; Department of Defense, 2018).

To counter rising Chinese influence, the United States Navy (USN) must plan and implement its overseas operations and diplomatic activities to maintain and strengthen U.S. alliances and partnerships (Department of Defense, 2020). This mission is central to Topic Sponsor (OPNAV N3/N5) lines of effort, naval component priorities within geographic combatant commands, and Navy sections within country teams. Effective partnership-building also requires a whole-of-government approach that incorporates the United States' superior military assets, including maritime security cooperation, with U.S. economic and diplomatic programs.

However, we lack roadmaps for how to effectively and efficiently couple naval activities and security assistance with economic programs. Existing research on sea power tends to marginalize naval diplomacy compared with the deterrent and compellent aspects of forward-deployed naval forces (e.g., Rowlands, 2012; Till, 2009). Conversely, most work on security cooperation and partner capacity-building has yet to emphasize the maritime domain (e.g., Reveron, 2016; Ladwig, 2017; Paul et al., 2013). Moreover, although recent research has developed promising comparative lessons on successful security cooperation and influence, it has focused narrowly on single regions and/or forms of operations (Meierding & Sigman, 2021; Ralph, 2021; Darnton, 2017). This project broadens the scope across regions and forms of USN engagement, while foregrounding the specifically maritime and naval aspects of influence-generation and partnership-building.

Our core question is, "How can the USN leverage its operations and activities to reinforce U.S. economic programs and enhance U.S. influence?" Using the comparative case study method, the research team examined USN activities, U.S. economic programs, and host government security interests in "indicator" countries in their respective regions: Chile in Latin America and the United Arab Emirates (UAE) in the Middle East. These are neither regional giants nor microstates, so findings from the cases are likely to be broadly generalizable. These are also states that have historically aligned more strongly with the United States than China, but are not steadfast U.S. partners in all domains. They therefore constitute important test cases for assessing whether USN engagement can move the needle on U.S. influence, in times of rising strategic competition.

To conduct the case studies, the research team consulted official U.S. government and host country documents, country reports, news sources, and quantitative data sets. Team members traveled to the host countries and interviewed U.S. country team members, partner nation flag officers and other officials, and leading experts. The research team simultaneously drafted separate case studies assessing the impacts of USN activities and U.S. economic activities on U.S. influence. They conducted a comparative analysis of the cases to identify the most productive U.S. naval and economic lines of effort and ways to overcome potential obstacles to interagency coordination.

Findings and Conclusions

The project's core finding, which has not been emphasized by previous research, is that the standard U.S. understanding of building capabilities and relationships, based on conventional assets for warfighting and deterrence within a robust alliance like NATO, frequently does not match partner nation security priorities outside of that context. In countries such as Chile and the UAE, where the operative concepts are economic development, international prestige and autonomy, and internal stability, platform sales and training are insufficient for building enduring, influential alliances and partnerships.

In Chile, naval cooperation with the United States remains robust, limited only by resource constraints—primarily economic on the Chilean side—and available assets and organizational bandwidth from the United States. Chile has long-term ambitions for fleet modernization and shipbuilding, and for global presence and prestige including across the Pacific; however, its primary security challenges are onshore and domestic, requiring institutional capacity-building across services and between uniformed and civilian leaders. Meanwhile Chinese economic and political inroads in Chile are concentrated in the private and civilian sectors. We recommend that the USN frame security cooperation efforts to contribute to Chilean economic development, prestige, and jointness and institutional capacity, and to preempt potential civil-military ruptures on questions of international alignment.

In the UAE, the supply of U.S. maritime security cooperation exceeds local demand, due to the small size of the UAE navy, the limited contributions that naval assets can offer to address the country's leading security concerns, and the navy's existing capacity to perform the core operations required of it. The UAE is also attempting to develop its indigenous defense industry, especially in the maritime domain, limiting navy and coast guard interest in foreign military sales. We recommend that the USN concentrate its maritime security cooperation in high-profile activities that enhance the UAE navy's reputation before domestic and international audiences, or that facilitate the UAE's transition to a post-hydrocarbon economy. The latter include collaboration in defense industrial research and development and strengthening the UAE's status as a leading transshipment center.

Chile and the UAE will continue to engage with China, given strong incentives to diversify their partnerships and offset perceived dependence on Washington, especially while anticipating U.S. retrenchment or resistance to selling advanced weapons systems. U.S. planners including within OPNAV N3/N5 (Topic Sponsor), naval components of combatant commands, and country teams, should not assume that historically strong military-to-military relationships are permanent firewalls against political pressures and Chinese economic ties, or that military relationships will automatically deliver political influence. Continued engagement is required.

To maximize efficiency and effectiveness, we recommend that Topic Sponsor (OPNAV N3/N5) and other security cooperation actors, such as the broader Navy Foreign Area Officer community, more creatively consider how to support partner nations' highest-priority issues, such as technology transfer and regional leadership. This will require careful grappling with unique local political contexts and challenges, and consideration of how these intersect with U.S. government policy priorities, American values, and nonmilitary lines of effort, especially when these touch sensitive questions of internal stability and domestic security.

Recommendations for Further Research

The study recommends that U.S. security cooperation efforts more creatively consider how to feed into partner nations' highest-priority issues, such as technology transfer and regional leadership roles and recognition. It notes that this type of engagement will require careful grappling with unique local political contexts and challenges, and consideration of how these intersect with U.S. government policy priorities, American values, and nonmilitary lines of effort, especially when these touch on sensitive questions of internal stability and domestic security. To implement these recommendations effectively in individual countries, U.S. naval commands and country teams require detailed knowledge of partner nations' leading security and economic concerns, as well as the local political context and challenges. These assessments may be conducted by country teams or external subject matter experts.

Implementing the country-level recommendations for Chile will involve carefully tracking the fragile and fluctuating political situation and not only seeking out affordable yet visible avenues for ongoing Chilean Navy engagements with the US Navy, but also identifying a broader range of stakeholders on issues of jointness, civil-military coordination, and defense and technology development whose perspectives and interests could affect Chilean decisions about international alignments.

Implementing the country-level recommendations for the United Arab Emirates (UAE) will require a deeper investigation of the viability of collaborating with the Tawazun Economic Council (the organization responsible for UAE defense procurement), engagement with UAE flag officers and other government officials to identify the areas of technical collaboration that are most attractive to them, and further examination of DP World's current activities, assets, and interests to determine whether they can be treated as a trusted partner.

Because a core conclusion of the project is that local political context is crucial for effectively targeting security cooperation outreach, one productive line of future research would extend the comparative analysis conducted in this project to other cases, to assess the findings' generalizability and scope conditions. In particular, this research should focus on identifying host countries' leading security cooperation interests. Foreign military sales is often assumed to top this list, but our project determined that prestige and economic development are often more attractive than platforms and capacity-building. Future research should especially focus on countries with lower levels of economic and military development than Chile and the UAE, or with more challenging political and ideological environments for U.S. partnership, since both factors might increase the temptations of Chinese partnerships and dilute U.S. influence.

Another line of future research might revisit Chile and the UAE two or more years after the initial study, in order to follow up on implementation of any recommendations and to evaluate how domestic political and economic shifts, evolving regional security challenges, force modernization efforts, and alterations to China's economic, diplomatic, and security initiatives might modify or re-validate our conclusions about the path to durable U.S. influence.

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NPS-22-N094-B: Securing Access to Sustain Presence and Overcome Chinese Influence in the Indo-Pacific

Researcher(s): Michael Malley, and Christopher Ketponglard

Student Participation: Maj Owen Bashaw USMC, and Maj Michael Valdez USMC

Project Summary

The purpose of this study is to assess whether, where, and how the Navy can leverage newly created policy tools to compete with China's efforts to secure access to ports and logistics facilities in the Indo-Pacific region. Traditional tools of security assistance and cooperation were not designed to meet the type of challenge posed by China's Belt and Road Initiative (BRI). However, in 2019, the United States established the Development Finance Corporation (DFC) and joined with Australia and Japan to create the Blue Dot Network. These initiatives promised resources for infrastructure development in lower income countries. Since then, others have been established. However, as new initiatives, their utility for achieving Navy-specific goals has not previously been examined.

This study identified U.S. and multilateral initiatives that are intended to promote infrastructure investments in the Indo-Pacific. It assessed the extent to which each initiative can be used to meet strategic goals through port and port-related investments. It found that most new initiatives lack resources, favor development priorities over strategic ones, and prioritize investment in sectors other than physical infrastructure.

However, the Development Finance Corporation is quite different. By law, it must consider development *and* foreign policy priorities. Its budget is growing rapidly and may reach $1 billion in FY23. Moreover, it makes investments in critical infrastructure, especially to enhance resilience to climate change in low and lower-middle income countries. Countries along the first and second island chains meet these criteria and seek these investments.

This study recommends that Navy leaders identify ports of strategic concern in this region, convey their priorities to the established interagency process known as the Development Finance Coordination Group; and advocate for investments that support these priorities.

Keywords: *Indo-Pacific, basing, access, ports, climate change, allies and partners, maritime strategy, distributed operations, Pacific Islands, Southeast Asia, Development Finance Corporation, DFC, Belt and Road Initiative, BRI*

Background

The purpose of this study is to assess whether, where, and how the U.S. Navy can leverage newly created policy tools to compete with Chinese economic and diplomatic efforts to secure access to ports and logistics facilities in the Indo-Pacific region. Traditional tools of security assistance and cooperation were not designed to meet the type of challenge posed by China's Belt and Road Initiative. However, in 2019, the United States established the DFC and joined with Australia and Japan to create the Blue Dot Network. These initiatives promised resources and official support for infrastructure development in lower income countries. Since then, others have been established. However, as new initiatives, their utility for achieving Navy-specific goals has not previously been examined.

The need for this study stems from a clash between two developments. One is the increasing reliance of U.S. maritime strategy on operational concepts that require the distribution of Navy and Marine Corps assets and personnel, especially in the Indo-Pacific region. These concepts include expeditionary advanced base operations, littoral operations in a contested environment, and distributed maritime operations. Strategic success depends on secure access to a range of ports and logistics facilities throughout this region.

The second is China's persistent effort to win control over ports around the world, especially in the Indo-Pacific. A report published by the Asia Society Policy Institute in 2020 argued that Chinese investments in Asian ports amounted to "weaponizing the Belt and Road Initiative" (Russel and Berger, 2020). In the same year, the Pentagon's annual China Military Power report highlighted the possibility that China may be using the BRI to expand its military access to overseas ports. It asserted that BRI "projects could create potential military advantages" and argued that China is trying to establish a "more robust overseas logistics and basing infrastructure to allow the PLA [People's Liberation Army] to project and sustain military power at greater distances" (Department of Defense, 2020, p. 128).

In response to these concerns, the United States and its allies developed comprehensive financial and diplomatic initiatives to counter Chinese influence. Although the naval services are not directly involved in these initiatives, they have a direct interest in where new investments are made. For that reason, this study examined the principal policies, institutions, and agreements that the U.S. government has adopted since 2018 to counter Chinese influence in ports and port-related infrastructure.

Findings and Conclusions

This study identified U.S. and multilateral initiatives that are intended to promote infrastructure investments in the Indo-Pacific. It assessed the extent to which each initiative can be used to meet strategic goals through port and port-related investments. It found that most new initiatives lack resources, favor development priorities over strategic ones, and prioritize investment in sectors other than physical infrastructure.

However, the DFC is quite different. By law, it must consider development and foreign policy priorities. Its budget is growing rapidly and may reach $1 billion in FY23. Moreover, it makes investments in critical infrastructure, especially to enhance resilience to climate change in low and lower-middle incomes countries. Countries along the first and second island chains meet these criteria and seek these investments.

This study found extensive overlap between the Navy's goals in its climate strategy and the DFC's goals. Each seeks to work with international partners to enhance the resilience of critical infrastructure. Crucially, many of the small Pacific Island states have identified climate change as their most pressing threat.

It also found extensive overlap between the Navy's prioritization of the Indo-Pacific and other U.S. government efforts to provide development assistance to low and lower-middle income countries in that region. Two efforts are notable. One is the Pacific Partner Strategy, which aims to bolster political, diplomatic, and economic ties with the small Pacific Island countries. This is supported by a partnership between the United States and key allies (Australia, Canada, Japan, New Zealand, and the United Kingdom) called "Partners in the Blue Pacific." The second is a 10-year program to strengthen Papua New Guinea, which is home to 90 percent of the people in the Pacific Islands and occupies a strategic location north of Australia and east of the Solomon Islands.

This study recommends that Navy leaders identify ports of strategic concern in this region, convey their priorities to the established interagency process known as the Development Finance Coordination Group, and advocate for investments that support these priorities. Projects that enhance the resilience of ports and port-related infrastructure to the impact of climate, especially in areas known as the first and second island chains, are most likely obtain support in the interagency process.

Recommendations for Further Research

To which ports would access be most valuable for the United States and its partners? Which of these face the most severe risks due to climate change? In these places, what types of infrastructure investment would be most useful for the U.S. Navy and most valuable to the host nation?

In the Pacific Partnership Strategy, the U.S. government has pledged to increase its diplomatic presence in the small Pacific Island countries and strengthen cooperation between those countries and groups such as The Quad (Australia, India, Japan, and the U.S.) and the Association of Southeast Asian Nations. What opportunities will this present for Naval diplomacy to strengthen the alliances and partnerships at the core of the maritime strategy?

The Philippines and Indonesia are large archipelagic states that are strategically located at the southern ends of the first and second island chains. Both countries have numerous ports on which they depend for economic development and national defense, but these are highly vulnerable to climate change. Which of their ports can benefit from U.S.-led investment to make them more resilient?

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NPS-22-N095-A: Addressing PRC "Three Seas Forces" Land and Resource Reclamation Efforts in the Indo-Pacific

Researcher(s): Michael Glosny, Michael Malley

Student Participation: No students participated in this research project.

Project Summary

In the last decade, China has employed its Navy, Coast Guard, and Maritime Militia to strengthen its "sovereign claims" and extend its maritime presence and control in the Indo-Pacific. This project, led by experts on China and maritime Southeast Asia, examined the best ways to push back on Chinese efforts in these maritime disputes, with the aim of crafting a more sustainable strategy to incorporate partners and allies in pushing back on China and deterring further aggression. The main findings and recommendations include:

1. The United States faces significant challenges and constraints in its efforts to push back on China
2. The U.S., together with its allies and partners, needs to be more proactive in preventing China from threatening U.S. interests and the regional order
3. The U.S. should focus on building partner capacity and resilience to enable these countries to stand up to China on their own
4. The U.S. Navy needs to think asymmetrically and creatively to combat this growing threat

Keywords: *China, South China Sea, gray zone, deterrence, coercion, great power competition, allies, allies and partners, maritime security, territorial disputes, Asia, East Asia, Indo-Pacific, Vietnam, Philippines, Malaysia, Taiwan, Indonesia, Free and Open Indo-Pacific*

Background

In the last decade, China has employed its Navy, Coast Guard, and Maritime Militia to strengthen its "sovereign claims" and extend its maritime presence and control in the Indo-Pacific. These activities have occurred in the East China Sea against Japan and in the South China Sea against several other claimants, most importantly including massive land reclamation activities. The U.S. government and U.S. Navy have tried to reassure allies and partners and conduct freedom of navigation operations in response, which have had mixed success in deterring and pushing back on China. In recent years, the U.S. military and U.S. Navy have intensified their focus on and preparation for a large-scale war with China over Taiwan and have devoted less attention to China's malign activities in the gray zones in the South China Sea. At the request of the Deputy Chief of Naval Operations for Operations, Strategy, and Policy, this project focuses on the relatively neglected area of the South China Sea and offers recommendations for the U.S. Navy and U.S. government.

This project examined the best ways to push back on Chinese efforts in these maritime disputes, with the aim of crafting a more sustainable strategy to incorporate partners and allies in pushing back on China and deterring further aggression. The research team included expertise on China and maritime Southeast Asia. This research effort examined recent successes and failures of regional claimants in how they have dealt with Chinese aggression, both alone, and with U.S. support. In addition to drawing on official policy statements and documents, academic and think tank publications, and newspaper reports, this project benefitted tremendously from discussions with officials at Office of the Chief of Naval Operations, Office of the Secretary of Defense-Policy, the Office of Naval Intelligence, Indo-Pacific Command, Pacific Fleet, and the U.S. Coast Guard.

This project offers conclusions and recommendations on how to best work closely with other regional allies and partners to craft a sustainable strategy to confront China and deter further aggression and gray zone coercion in the South China Sea. It also examined the types of cooperation most desired by our allies/partners and what would be seen as too provocative. Further, it examined which types of support are most likely to deter China.

Findings and Conclusions

The United States faces significant challenges and constraints in its efforts to push back on China. First, given the U.S. military and U.S. Navy's focus on the potential for large-scale war over Taiwan, there is no real war plan for the South China Sea, and Indo-Pacific Command has not been given a requirement to develop a plan to counter gray zone operations in the South China Sea. The lack of requirements and authorities have contributed to a more reactive approach. Second, compared with China's "Three Seas Forces," the United States and U.S. Navy lack the resources to compete with what China can deploy.

Third, there are significant differences between the U.S. and allies and partners in what actions most effectively deter China in the South China Sea. The U.S. usually defers to allies and partners as it wants them to be in the lead, but they are often unclear in what they want from the U.S., what they will provide, or how they will act in potential crisis situations. Allies and partners often want specific responses on how the U.S. will respond, but the U.S. usually prefers to maintain flexibility and freedom of action. All of this complicates coordination in how to respond to China's malign activities, and even more in how to communicate to China that there is a clear and coordinated threat that is more likely to deter Chinese actions.

The United States and its allies and partners have mostly been reactive in the South China Sea and have only taken action or made threats after China has already changed the status quo through its malign activities. The U.S., together with its allies and partners, needs to be more proactive in preventing China from threatening U.S. interests and the regional order.

Given China's coercive actions towards other claimants, there seems to be a greater willingness by these countries to push back on China, but they often lack the capabilities and capacity. The U.S. should focus on building partner capacity and resilience to enable these countries to stand up to China on their own. Such support would not only include sharing our assets to enable maritime domain awareness and intelligence, surveillance, and reconnaissance, but also help our allies and partners to develop their own capacity to combat China's persistent coercion.

The U.S. Navy needs to think asymmetrically and creatively to combat this growing threat. Especially given U.S. resource constraints, trying to counter China symmetrically with equal presence is impossible. This requires more flexible thinking and a broader approach to leverage assistance from allies and partners, but also to explore the possibility of commercial companies, unmanned systems, and advanced technology to try to provide a more persistent presence in the South China Sea, which is more likely to prevent China from taking advantage of weaknesses. Much of the capabilities can be acquired or redirected at a relatively low cost, and resources will not be diverted away from preparation for a potential large-scale war with China over Taiwan.

Recommendations for Further Research

The following areas of future research will help deepen knowledge in how to best deter and push back on China's malign activities in the gray zones, especially in the South China Sea.

Determine specific actions that we wish to deter or prevent in the South China Sea. To date, most statements from the U.S. government and U.S. Navy refer to opposing Chinese challenges to the Free and Open Indo-Pacific and opposing China's challenges to the status quo. As most historical cases of effective deterrence include a clear statement of the actions that the adversary should not undertake, greater consideration and discussion of the specific actions that we wish to deter is necessary for stronger and more effective deterrence.

Conduct more research not only on how to better coordinate with our allies and partners, but also on how to build their resilience so they can stand up to China and deter Chinese challenges more effectively on their own. On the earlier recommendation of determining specific actions to deter, research needs to be conducted on the specific actions our allies and partners wish to deter as well, and then comparisons are necessary between U.S. priorities and priorities of allies and partners. To improve coordination with our allies and partners, research and discussions are needed both on what they would like the U.S. to do to respond to China and hopefully prevent China from taking coercive actions, but also on what activities from the United States would be seen as counterproductive or even provocative. With one of the main findings and recommendations being to enhance the resilience of our allies and partners, more specific discussions need to occur with our allies and partners about the best ways to do so.

Most research has understandably focused on deterrence failures and cases in which China successfully used malign activities and gray zone tactics to change the status quo in its favor, but more research is needed on cases of apparent successful deterrence of China. Starting under President Obama, the U.S. has been clear and forceful in trying to prevent China from doing land reclamation on Scarborough Shoal, which has arguably been a case of successful deterrence. More research is needed on this specific case and the elements that made it successful and other cases of apparent success, with attention paid to whether U.S. threats prevented China from taking such actions or if China was not interested in taking such actions at the time.

Even with a narrower conception of gray zones in the maritime domain that we use in this project, successful deterrence and pushing back on China requires a whole-of-government approach and more cooperation with other government agencies. Although this is a U.S. Navy project, more research is required on the role of the U.S. Coast Guard, both in undertaking actions itself in the South China Sea and in working with the coast guards of allies and partners to enhance their resilience and ability to push back on China by themselves.

References

None

NPS-22-N117-A: Leverage AI to Learn, Optimize, and Wargame (LAILOW) for Strategic Laydown and Dispersal (SLD) of the USN Operating Forces

Researcher(s): Douglas MacKinnon, Walter Kendall, Riqui Schwamm, and Ying Zhao

Student Participation: No students participated in this research project.

Project Summary
The Secretary of the Navy disperses Navy forces in a deliberate manner to support Department of Defense (DoD) guidance, policy and budget. The current strategic laydown and dispersal (SLD) process is labor intensive, time intensive, and less capable of becoming agile for considering competing alternative plans. SLD could benefit from the implementation of artificial intelligence (AI). Our focus was guided by the inquiry of learning:

1. How does Navy weigh competing demands for naval forces to determine an optimal dispersal of operating forces?
2. How does the Navy optimize force laydown to maximize force development and force generation efficiency?

We introduced a relatively new methodology to address these questions which were recently derived from an earlier Office of Naval Research-funded project that combined deep analytics of machine learning, optimization, and wargames. This methodology is entitled LAILOW, which encompasses Leverage AI to Learn, Optimize, and Wargame (LAILOW) (Zhao and Mata, 2020). We began here by collecting data then employed data mining, machine learning, and predictive algorithms to perform artificial intelligent analysis to learn about and understand the data. This data included historical, phased, force deployment data among others to learn patterns of what decisions were made and how they were executed. We then developed a stand-alone set of pseudo data that mimicked the actual, classified data so that experimental excursions could be performed safely. We also limited our data to include ships. Our efforts produced a first-ever, relative, and optimal score, from a wargame-like scenario (Zhao and Nagy, 2020) for every available ship that might be moved. The score for each ship increases as fewer resources are required to fulfill a strategic laydown and dispersal (SLD) plan requirement to move that ship to a new homeport. This not only produced a mathematically optimal response (Zhao, et al., 2020), but also enabled the immediate comparison between competing or alternate ship movement scenarios that might also be chosen.

Keywords: *artificial intelligence, AI, machine learning, optimization, strategic laydown and dispersal, SLD, data mining*

Background

The laydown and dispersal of U.S. Naval forces requires manual manipulation of data via weekly Working Groups, which is manpower intensive, and only presents one option to the Chief of Naval Operations and the Secretary of the Navy for consideration. The current SLD process takes one full year to develop and is not responsive to changes in the operating environment or strategic guidance. For example, there is no mechanism to leverage existing data resources to monitor plan execution and track progress toward completion. The SLD plan needs more than just simple process revision; it requires wholesale re-imagining to be an Information Age decision support tool. The 10 years of projected force laydown optimization problem can be overwhelming.

More specifically, this is based on a memo from RDML T.R. Williams, Director for Plans, Policy, and Integration (N5) for Deputy Chief of Naval Operations for operations, plans, and strategy (N3/N5) (Williams, 2021), who is teaming with industry and academia to modernize the SLD process. The challenges are described in the following phases.

- **Descriptive Phase - What decisions were made?** This phase is focused on developing a new database utilizing modern data analytics to display information in a shareable website. The current SLD database exists on a standalone computer with a single user's access in the Pentagon requiring manual update. This phase's end state is a cloud-based SLD database accessible to the SLD working group that offers permission controls and features improved analysis and display functions. Estimated time to completion: 6-12 months.

- **Diagnostic Phase - How are we executing decisions that were previously made?** This phase is focused on improving our ability to analyze previous decisions. Current SLD Report Cards require extensive work outside routine SLD working group effort to compile historic data and reassess it manually. The end state is a tool that automatically tracks and reports execution of previous SLD decisions. Estimated time to completion: 12-18 months.

- **Predictive Phase - How are we making decisions? What happens if I make a different decision?** This phase's end state is an Excursion Modeling Tool. The goal is to develop a decision support tool that uses existing authoritative data and model SLD excursions to rapidly and more accurately assist decision making. Estimated time to completion: 18-36 months.

- **Prescriptive Phase - Are we making the right decisions?** This phase's end state will utilize an AI algorithm to take the SLD calculations and other inputs to evaluate the SLD plan and create an optimized plan by including global and theater posture and time phased force deployment data (TPFDD) into the calculations. Estimated time to completion: 36-60 months.

N52's goal is to radically update the SLD process with a cloud-based SLD database, to utilize "big data analytics" and AI to aid decision making and reduce manpower requirements to focus on the strategic basis and integration of the SLD Plan for improved efficiency and better-informed decision making.

Findings and Conclusions

Our efforts produced a first-ever, relative, and optimal score, as derived from a wargame-like scenario, for every available ship. The score for each ship increases as fewer resources are required to fulfill an SLD plan requirement to move that ship to a new homeport. This not only produced a mathematically optimal response, but also enabled the immediate comparison between competing or alternate ship movement scenarios that might be chosen instead.

Our original understanding of how the Navy scores these potential ship movements was improved through our exploration of this topic. The Navy considers variables such as available maintenance, pier space, and required schools, as well as the distance between the ship's present location and its potential new homeport. Additionally, each ship overseas must return to the continental United States within ten years, and each one fulfills tactical and strategic requirements that are also considered. There are also unseen political preferences that can also outweigh numerically based resource requirements.

We anticipate our findings to guide the way forward toward further exploration in this area through our suggested methodology. This would likely save time and energy of the decision makers and offer otherwise undiscovered potential alternative solutions to future SLD plans.

Recommendations for Further Research

More can be accomplished to consider how machine learning and artificial intelligence (AI) methodologies might improve the strategic laydown and dispersal (SLD) process to optimize force laydown to maximize force development and force generation efficiency. Having shown our mathematical ability to solve a smaller problem using artificial data, we suggest the next steps may include the development of an electronic model of the SLD process into a minimum viable product (MVP) that can assist future SLD development and justify potential movement scenarios and their decisions consistently.

Two primary research questions guiding this future research could be:

1. How can a proof of concept, electronic model, be developed to help decision makers standardize the SLD process?
2. How can SLD scenario development and scenario comparisons be more readily made in terms of risk and cost?

In Phase I, the performing team demonstrated the feasibility of the methodologies of leveraging AI to learn, optimize, and wargame (LAILOW), including predictive algorithms that learn. In consideration of future efforts, we envision a more integrated, coherent, and large-scale, deep analytics effort leveraging methods that link to existing data sources to more easily enable the direct comparisons of potential scenarios of platform movement considered through the SLD process. The resulting product could facilitate decision makers' ability to learn, document, and track the reasons for complex decision making of each SLD process and identify potential improvements and efficiencies.

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Memo from RDML T.R. Williams, Director for Plans, Policy, and Integration (N5) for Deputy Chief of Naval Operations for operations, plans, and strategy (N3/N5), 2021.

NPS-22-N138-A: Prospects for Deterrence, Escalation, Coercion and War in the Indo-Pacific

Researcher(s): James Russell, Wade Huntley, James Wirtz, and Michael Malley

Student Participation: LT Joshua Hudson USN, and LT Dan Feeney USN

Project Summary

This project marks the second year that the PI and a team of researchers assess the prospects for war in the Indo-Pacific. The purpose of the assessment is to inform the Navy's strategy in this vital theater of operations. Drawing upon the theoretical literature, as well as analysis of contemporary geopolitics, this project examines how regional actors assess the prospects for war, specifically their attitudes towards deterrence and escalation management on the use of force at sea, and the implications for possible conflict with Indo-Pacific competitors. The study highlights the need for the Navy to unpack the geopolitical complexities of this region that are inextricably intertwined with the uncertainties of structuring a deterrent force that can help create a political environment to minimize the chances of regional war. This complex endeavor is more of an art than a science.

The findings in this study are germane to the development of America's maritime strategy throughout the region. The project finds that the Navy must develop a new set of assumptions to guide its approach to alliance management, regional partnerships, as well as the challenges posed by all-domain conflict across different warfare spectrums. All of these factors must figure into the Navy's long-range planning system that addresses fleet design, force structure, and weapons design across the warfare domains. Moreover, the Navy must reexamine and recast Cold War–era assumptions about deterrence based on strategic nuclear weapons to reflect the complexities of all-domain conflict in which it will be increasingly difficult to segregate the levels of war (strategic, operational, and tactical). Finally, this project finds that the Navy must plan for uncertainties stemming from the introduction of advanced weapons technologies by regional states into the strategic environment.

Keywords: *deterrence, escalation ladder, maritime strategy, naval power, arms races, Indo-Pacific, coercion, nuclear weapons*

Background

After a hiatus of a little more than two decades, state-on-state competition at sea is again a central issue of international security. Today, the US-led maritime order and the freedom to use the ocean as a vast maneuver space to access different theaters stand contested. Nowhere is the urgency to meet state-on-state competition at sea stronger than in the Indo-Pacific region, where freedom of navigation is being challenged by regional states' continuous investments in military power and their renewed political will to use it. Yet, in the Indo-Pacific, naval power is a requirement for, and a propeller for further expansion of, a great variety of missions, encompassing widening constabulary and law-enforcement activities aimed at the management of maritime boundary delimitations and territorial disputes. These missions stand at what might be regarded as the low end of potential conflict scenarios, which range all the way up to open warfare on the high seas.

This study sits at the nexus of the central challenge facing the United States Navy in the 21st century. The Navy N3/N5 organization requires answers to the following questions as addressed in this report:

1. How can the Navy best posture itself to deter and, if necessary, fight a war in the Indo-Pacific's vast maritime domains?
2. How can the Navy best prepare itself for a maritime war at sea in the Indo-Pacific?
3. What role can the Navy play in building political and security partnerships to deter and, if necessary, fight a war in the Pacific?

This study addresses these questions by drawing upon the security studies and international relations literature on the phenomena of deterrence, conflict escalation, coercive political strategies, and arms races. The research team drew upon this literature as a baseline to analyze the Navy's problem set in posturing itself across the domain. It then makes recommendations about steps the Navy should take to address the strategic environment.

Findings and Conclusions

This study finds that, first, the Indo-Pacific is in the midst of a region-wide naval arms race in which various states are acquiring advanced conventional and nuclear systems. Most of these systems are offensive. These emerging force structures across the region affect the military balance, which is a foundational component of the deterrence framework. Second, the study finds that China in particular appears intent on linking its growing military capabilities to a coercive political framework in which it is indirectly applying the threat of force to achieve its political objectives. Third, the study finds that regional states are all gradually embracing the idea of the "all domain" war in which the next conflict could involve cross-domain operations in cyber, space operations, and information/social media interactions, in addition to kinetic operations underwater, on the ocean's surface, and in the skies.

At the outset, the study suggested that the Navy needs to relearn some of the lessons from the Cold War when integrating conventional and nuclear weapons into its operational planning and when linking its force structure with ideas of wartime escalation management and nuclear deterrence. This study confirms that the Navy needs to dust off its Cold War–era approaches and consider such issues as (1) the appropriate mix of nuclear and conventional weapons carried aboard ships; (2) developing plans to integrate its systems for cross-domain operations to reflect the requirements of the "all domain" war; and (3) building political relationships with regional partners that include them in the planning process that addresses the range of potential conflict scenarios across the Indo-Pacific domain.

The literature on deterrence and nuclear weapons and their role in national security strategy is a good starting point for the Navy to develop a conceptual framework to apply naval power in this complex strategic environment. This can be done in part through education of the mid- and senior-level leaders facing these challenges. This conceptual framework can form the basis for exercises and experiments to flesh out the ideas as applied in different regional scenarios.

Recommendations for Further Research

A central finding of this study is that the Navy and the United States need much greater fidelity on the dynamics of deterrence across the vast Indo-Pacific region. Stated differently, given the complexities of the region's geopolitics, there is much that the Navy does not know about how deterrence does and does not work. The findings of this report suggest that the Navy investigate how to further operationalize strategies of deterrence across the various domains of conflict: land, sea, air, undersea, cyber, and information. This can be done through a series of table-top exercises and/or visits of research teams to key friends and allies across the area of operations to establish common understandings on these critical questions of deterrence, coercion, and potential escalation to all-out war across the region.

References

None

NPS-22-N155-A: Competition with Iran in a Constrained Resource Environment

Researcher(s): Afshon Ostovar, and Christopher Ketponglard

Student Participation: No students participated in this research project.

Project Summary

The turn toward great power competition (GPC) will require tough choices regarding the U.S. Navy's investments and global force posture. That includes in the Middle East, where the threat posed by Iran remains persistent. Deterring Iran's malign behavior has been difficult. This report examines why, and focuses on what motivates Iran's grand strategy and the capabilities it relies on to advance that strategy and challenge its adversaries. It further explores the recent trajectory of Iran's malign behavior in the greater Persian Gulf region, particularly in the maritime domain, to understand how that behavior is designed to further political and strategic aims. Understanding the drivers of Iran's behavior, and its appetite for risk taking, is important, and factors that should be considered when thinking through any potential shifts to U.S. maritime strategy. The report concludes with some brief concluding recommendations on how the Iranian challenge might be managed by designing assistance to better counter Iran's chief strategic capabilities—missiles and drones. In order to address the challenges posed by those means, force posture and partner capacity building efforts in the region should be deliberately designed to counter and defeat them.

Keywords: *Great Power Competition, GPC, Middle East, strategy, deterrence, United States Central Command (USCENTCOM), Iran, Persian Gulf, Arabian Gulf, Strait of Hormuz, ballistic missiles, unmanned aerial vehicles (UAV), drones, grey zone conflict*

Background

This study was borne out of a critical question: how to do more with less. It is aimed to help inform the Navy's strategic and planning considerations regarding how best to deploy the fleet in an era of great power competition. To that end, the study looks at the Middle East, a region that continues to pose threats to U.S. interests and military operations, primary among them: Iran.

Deterring Iran has hinged on the notion that a continuous American maritime presence would prevent Iranian aggression at sea and more broadly. This effort has been mostly successful. There is no doubt that the U.S. Navy presents an insurmountable challenge to Iran, and one that Iran's leadership must consider in operational planning and strategic decision-making. However, it is also clear that, while Iran's behavior might be constrained, it has nonetheless pursued an aggressive line toward U.S. forces, and toward its neighboring adversaries. The net effect is an Iran deterred in part but not in whole.

In order to better discourage Iran's malign behavior, we must first have a better understanding of Iran's behavior. This report pursues the latter aim by examining Iran's grand strategy, the capabilities it relies on to advance that strategy, and the recent trajectory of its aggressive behavior in the greater Persian Gulf region. Understanding the drivers of Iran's behavior, its appetite for risk taking, and the capabilities that enable it to effectively challenge regional partners, is important, and are factors that should be considered in the Navy's strategy and future planning efforts concerning the Middle East.

The purpose of this study is to build on our knowledge of the Iranian threat by examining its recent cases of aggressive behavior, especially in the maritime domain. To that end it builds on previous work by the author, and two articles in particular: "The Grand Strategy of Militant Clients: Iran's Way of War." Security Studies, vol. 28, no. 1, 2019; and, "Iran, its Clients, and the Future of the Middle East: The Limits of Religion," International Affairs, Vol. 94, no. 6, 2018: 1237-1255.

The research for this study was focused on unclassified literature and news reporting, including Persian language sources such as official statements; published interviews with military leadership; government publications; military publications; and semi-official news sources. The information gleaned from those sources was used to establish baselines for Iranian strategy and behavior, and the effectiveness and limits of current deterrence efforts. Short case studies were developed to analyze Iranian attacks in the region. These case studies helped determine the tactics Iran relies on, the vulnerabilities those tactics pose to U.S. and partner interests, and the capabilities required to deter, counter, or prevent such attacks from succeeding. By establishing the threat posed by Iran, the capabilities and tactics used by Iran, and the trend lines of Iran-related malign incidents, we were able to identify what capabilities are most needed to counteract and deter Iran and which capabilities are less necessary.

Findings and Conclusions

This study finds that Iran relies on two main areas to exert pressure against U.S. forces and partner states: missiles and drones. Those capabilities have been used by Iran and its proxies with strategic effect against U.S. forces in the region, and against partner states in the region. In order to dissuade Iran from using these capabilities toward coercive ends, partner states must possess the means to counter these capabilities directly. The U.S. Navy is in the best position to help partner states redesign their defensive efforts, to include spending and force development, to that end.

This study and its core findings will aid in Naval Operations for Operations, Plans and Strategy's (N3/N5) near-, mid-, and long-term planning processes and strategy concerning the problem set posed by Iran. It will further inform N3/N5's planning efforts regarding force posture and operations in the Middle East, and by extension, sharpen thinking on the regional implications of plans and strategy regarding great power competition.

Drawing from the study's findings, N3/N5 planners and strategists should consider directly linking the U.S. Navy's force posture and partner capacity building efforts in the broader Persian Gulf region with countering Iran's specific capabilities of concern, especially missiles and drones. Curbing Iran's ability to use those capabilities, by facilitating an effort to develop a sustainable architecture to counter them in the region, will better constrain Iran's behavior and better limit the effectiveness of its aggression.

Recommendations for Further Research

This study has identified the problem that Iran's chief strategic capabilities—missiles and drones—pose to U.S. forces in the Middle East and regional partner states. In order to address the challenges posed by those means, force posture and partner capacity building efforts in the region should be deliberately designed to counter and defeat them. Further research should therefore examine the potential weapons systems, force mixes, and fleet deployments required in the region to develop a sustainable architecture to nullify Iran's current capability advantage.

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NPS-22-N249-A: Enhancing US-Japan-Taiwan Cooperation/Deterrence Efforts for Potential Taiwan Contingencies

Researcher(s): Michael Glosny

Student Participation: LT Austyn Sutton USN

Project Summary

This project examines the recent evolution of U.S.-Japan alliance coordination in potential Taiwan contingencies and offers recommendations on how to enhance it. The U.S.-Japan alliance remains one of

the strongest pillars for peace and stability in the Indo-Pacific, but ambiguities in the policies of both countries regarding responses in Taiwan contingencies and insufficient coordination between the U.S., Japan, and Taiwan may undermine deterrence and encourage beliefs in Beijing that military operations may succeed. As COVID restrictions on travel prevented conducting discussions with Japanese officials and experts and American officers in Japan, this project has relied on scholarship of experts and gathered data from official sources and news coverage. The project has three main findings: 1) despite new signals from Japan about being serious in its military modernization and new focus on the Taiwan issue, the Japanese official position remains ambiguous in terms of whether or not it would grant access to U.S. bases and if (and how) it would directly participate in military responses to a Taiwan contingency; 2) although Japan remains sensitive to directly antagonizing China, the growing fears over an attack on Taiwan have opened up more possibilities for official and unofficial discussions of how to improve coordination, while maintaining a division of labor approach; 3) Japan's response will be shaped by domestic legal and political judgments, which may constrain or delay Japan's response. These findings suggest that even though Japan has embarked on a new military modernization and there is greater interest in Taiwan issues, which does provide opportunities for enhanced cooperation and coordination, Japan's policy ambiguity and legal and political constraints on support may delay Japan's decision and result in lower levels of military participation than many planners currently assume.

Keywords: *Taiwan, China, United States, Japan, U.S.-Japan alliance, deterrence, alliance, bases, naval diplomacy*

Background

China's military modernization and regional aggression, combined with a return to power of the more independence-leaning Democratic Progressive Party government in Taiwan, has led to greater tension and possibility of war across the Taiwan Strait. With the balance of military power shifting in China's direction, and concerns that Xi Jinping may be growing impatient, many experts have voiced concern that China is more likely to use force against Taiwan in the near-term. Japan is a major regional power with shared interests in preventing Chinese regional domination and the U.S.-Japan alliance is one of the cornerstones in maintaining stability and enhancing deterrence in the Indo-Pacific. Despite the importance of US military bases in Japan for deterrence and warfighting in Taiwan contingencies, the role of Japan and the U.S.-Japan alliance in Taiwan contingencies remains understudied. As the challenge from China becomes greater, ambiguity and uncertainty in the role of the U.S.-Japan alliance in Taiwan contingencies may undermine deterrence across the Taiwan Strait. To enhance deterrence across the Taiwan Strait and to strengthen coordination in the event of a crisis or conflict, this project examines ways to enhance U.S.-Japan-Taiwan coordination.

This project aims to identify ways to enhance and deepen U.S.-Japan-Taiwan coordination in response to potential military contingencies in the Taiwan Strait. To achieve this objective, the project addresses the following questions:

- What is the evolution of and current role of the U.S.-Japan alliance in Taiwan contingencies?
- What are the best areas to pursue greater coordination between the U.S., Japan, and Taiwan in Taiwan contingencies?
- What are the greatest impediments to deeper cooperation and coordination?

The data collected and analyzed for this project builds on the existing scholarship on the U.S.-Japan alliance and Taiwan military contingencies. This project will also draw on evidence of new official and unofficial discussions and debates in Japan about Taiwan that have been sparked by greater Japanese concerns about the threat from China and a potential attack on Taiwan. The biggest methodological weakness and challenge for this project is that COVID travel restrictions prevented me from taking a research trip to Japan to have discussions with Japanese officials and experts and U.S. military officers operating in Japan. Hopefully future projects and research will allow such travel, which will produce more complete data and findings, and lead to improved policy recommendations.

Findings and Conclusions

This project has three main findings.

First, despite new signals from Japan about being serious in its military modernization and new focus on the Taiwan issue, the Japanese official position remains ambiguous in terms of whether it would grant the U.S. access to American bases and if (and how) it would directly participate in military responses to a Taiwan contingency. Although American and Japanese leaders referred to Taiwan in an April 2021 joint statement, for the first time since 1969, this did not represent a radical shift in position. For a Japan that wants to maximize benefits from relations with both America and China, this would be the true "nightmare scenario" for Japan.

Second, although Japan remains sensitive to antagonizing China, the growing fears over an attack on Taiwan have opened up more possibilities for official and unofficial discussions of how to improve coordination, while maintaining a division of labor approach. The division of labor approach would prevent Japan from directly attacking China in combat but would allow Japan to support and enable American combat efforts. Beyond granting access to use of bases, Japan's defense of its islands to its Southwest, providing intelligence on Chinese aircraft, surface ships, and submarines would enhance U.S. combat power in defense of Taiwan.

Third, Japan's response will be shaped by domestic legal and political judgments, which may constrain or delay Japan's response. Whether a Chinese attack on Taiwan is judged to be a "survival threatening situation" or merely an "important influence situation," will determine how much assistance Japan could legally provide. It is possible, and even likely, that there would be considerable domestic debate within Japan, delaying Japan's decision on granting access to bases and on whether to participate in the defense of Taiwan.

This project has directly informed how the U.S. Navy and OPNAV N3/N5 should incorporate its most important ally in the Indo-Pacific in its planning for the most challenging high-end contingency. The following recommendations will enhance alliance coordination and inform future official naval engagements, discussions, and exercises with Japan.

The United States and Japan should deepen their understanding of "prior consultation," as this will be required for U.S. military access to U.S. bases. What are the mechanisms and content for such consultation?

Given the importance of rapid reaction in a Taiwan contingency, even though Japan's level of support and participation is a political decision that will be made by the prime minister, the U.S. and Japan should establish chains of command for a division of labor that will allow them to coordinate a response at the strategic, tactical, and operational level.

Although much of the military planning for Taiwan contingencies "plans in" Japan, U.S. planners need to consider the possibility of a delayed response or lower levels of Japanese assistance.

With the ambiguity of Japan's commitment, military planners and military analysts should employ a spectrum approach including a minimum level of Japanese support and a maximum level of Japanese support, rather than assuming Japan will completely support the United States.

Recommendations for Further Research

Given China's continued military modernization and the strong likelihood of China's intimidation of Taiwan, there will continue to be an urgent need to deepen our understanding of the role of Japan in a potential Taiwan contingency and improve deterrence of China's use of force. Moreover, with the lifting of COVID restrictions, further research can address some of these issues by meeting with Japanese officials and experts and U.S. military officers in Japan. Several areas of further research and focus include:

- Tracking future evolution of Japan's understanding of the China threat, the importance of Taiwan, and debates and new policy statements on the Taiwan situation and the role of Japan and the U.S.-Japan alliance in managing it.
- Examining the implementation of Japan's recently announced plans for military modernization and increased defense spending.

Given that Japan's level of support and participation will largely be determined by political leaders and not military leaders, following the evolution of views on China and Taiwan amongst these leaders is critical. Are there differing views and factions within the ruling Liberal Democratic Party? How do other political parties view the issue of Taiwan and military involvement? What is the level of public support in Japan for Japan allowing U.S. access to bases and Japanese military involvement?

The future trajectories of Taiwan-Japan relations also needs to be studied. Although the ruling Democratic Progressive Party is most important currently, members of the Guomindang are powerful in the legislature and could return to power in future elections. Taiwan public views on Taiwan-Japan relations and the potential military involvement in a Taiwan contingency should also be examined.

As the main goal of this research and recommendations is to more effectively deter China from attacking Taiwan, Chinese views on the level of coordination between the U.S. and Japan in a potential Taiwan contingency is supremely important and needs to be analyzed, though it is difficult to study directly. Although China has complained about Japan's return to "militarism," how do Chinese experts assess the level of coordination in the alliance and the likelihood of Japanese involvement in a potential Taiwan contingency? Do they view recent changes in Japanese views on Taiwan as representing big changes or just empty talk?

References

None

NPS-22-N257-A: Strategy and Conventional-Nuclear Integration for the Navy

Researcher(s): James Russell, James Wirtz, and Jeffrey Larsen

Student Participation: LT Joshua Hudson USN, and LT Dan Feeney USN

Project Summary

The Navy is confronting a new era of potential war on the high seas against two-nuclear armed adversaries: Russia and the People's Republic of China. Russia is threatening to use nuclear weapons in its war against Ukraine—one of the theaters of which includes the Black Sea. China has been engaged in a series of operations across the Indo-Pacific domain designed to create a political environment favorable to the PRC. The People's Liberation Army-Navy has been instrumental to this effort across the Indo-Pacific's maritime domains. The Navy today thus confronts the prospect of maritime conflict in these theaters with nuclear states. It must address how and under what circumstances it will integrate its conventional and nuclear weapons across the full spectrum of conflict, ranging from non-kinetic, gray zone–type encounters all the way up the escalatory chain to a nuclear exchange. At present, the Navy (and the other services) conceptualize warfare in discrete areas: conventional, chemical, biological, cyber, and nuclear. This project addresses the Navy's challenges in developing a coherent conceptual framework that recognizes the linkages between all these domains of warfare, with particular emphasis on nuclear and conventional weapons.

Keywords: *nuclear weapons, conventional weapons, warfighting concepts, escalation ladder, deterrence, maritime strategy*

Background

Traditional operational, tactical, and intellectual divisions between different domains of warfare have been all but eliminated in the modern era. It is increasingly apparent that war has been and is being waged in many different domains simultaneously: kinetic conventional operations on land and sea and in the air, information operations across communications domains, cyber operations that affect military and non-military targets, and space operations that reach across all domains. Nuclear weapons are certainly part of this framework, sitting as the ultimate "guarantor" of escalation dominance to states with these weapons. Within these domains, there has always been a kind of "firewall" between using nuclear and conventional weapons in war, with nuclear weapons thought of as discrete weapons with discrete (and strategic) capabilities that would only be employed in the direst circumstances.

That said, this "firewall" between nuclear and conventional weapons conceptually and operationally has remained somewhat tenuous. During the Cold War, the Western alliance envisioned nuclear weapons as part of an "escalation ladder" that would deter the Soviet Union from invading Western Europe and, in the event of war, would allow the West to prevail using nuclear weapons if necessary. The Navy's role in this history is of central importance. During the Cold War, it routinely deployed thousands of nuclear weapons at sea, ranging from tactical to strategic weapons (in the case of submarine-launched ballistic missiles). Like the other services, the Navy participated in the fielding and deployment of these weapons to its operational components.

The global strategic landscape has changed since the end of the Cold War, and the Navy's conception of the role played by nuclear weapons must be rethought.

This study sits at the nexus of the central challenge facing the United States Navy in the 21st century. The Navy N3/N5 organization requires answers to the following questions that are addressed in this report:

1. How can the Navy best posture itself to integrate nuclear and conventional weapons across the different domains of war?
2. Does the Navy need a different mix of nuclear and conventional weapons to preserve and strengthen integrated deterrence?
3. What is the appropriate relationship between conventional and nuclear weapons in the structure of integrated deterrence as enunciated by the National Command Authority?

To answer these questions, the study draws upon the security studies and international relations literature that addresses the issues of deterrence, conflict escalation, coercive political strategies, and arms races. The research team uses this literature as a baseline to analyze the Navy's problem set in posturing itself across the domain. The study recommends steps that the Navy should take to address the strategic environment with respect to the integration of conventional and nuclear weapons.

Findings and Conclusions

This study finds that the Navy needs to relearn some of the lessons from the Cold War, when it integrated conventional and nuclear weapons into its operational planning and linked its force structure with ideas of wartime escalation management and nuclear deterrence. This study confirms that the Navy needs to consider its Cold War–era approaches to consider such issues as:

1. the appropriate mix of nuclear and conventional weapons carried aboard ships; and
2. developing plans to integrate its systems for cross-domain operations that reflect the requirements of the "all domain" war that links conventional and nuclear weapons.

The literature on deterrence and nuclear weapons and their role in national security strategy provides a good starting point for the Navy to develop a conceptual framework to apply naval power in this complex strategic environment. This can be done in part through education of the mid- and senior-level leaders facing these challenges. This conceptual framework can form the basis for exercises and experiments to explore the ideas as applied in different regional scenarios.

Recommendations for Further Research

A central finding of this study is that the Navy and the United States need much greater fidelity on the dynamics of the relationship between different warfare domains. Stated differently, there is much that the Navy does not know about how deterrence does and does not work as it contemplates the integration of conventional and nuclear weapons. The findings of this report suggest that the Navy investigate how to further operationalize strategies of deterrence across warfare domains. A means to such an end can be accomplished via table-top exercises and/or visits of research teams to key friends and allies across the geographic commands to establish common understandings on nuclear deterrence and multi-domain war.

References

None

N4 - Fleet Readiness & Logistics

NPS-22-N050-A: Posturing Spares for Great Power Competition

Researcher(s): Margaret Hauser, and Geraldo Ferrer

Student Participation: LT Kionna Myles USN, LCDR David Connell USN, LCDR Keith Loedeman USN, and LCDR William Shields USN

Project Summary

Effectively posturing spares is essential to support forces for Great Power Competition. The purpose of this project was to study the effectiveness of spare-posturing strategies towards the improvement of operational availability by incorporating additive manufacturing (AM) into the supply chain. This study considered two situations. The first analyzed the naval aviation consumable spare part supply chains inclusive of AM as a supply source to fulfill orders within the United States Indo-Pacific Command (USINDOPACOM) sustainment network. These results would offer more definitive impacts that AM could have on naval aviation consumable repair parts lead time, especially for orders historically filled via contracts with longer lead times. This leads to the conclusion that the sooner we can operationalize AM to produce safe parts while running in parallel with traditional order fulfillment methodologies, the sooner we can see lead time improvements enterprise-wide even while AM-fulfillment only comprises a small fraction of orders. The second situation investigated how to better sustain the Phalanx Close-in-Weapon-System (CIWS) on guided missile destroyers (DDGs) in contested environments. This work found that the capabilities of 3D printing offer the Navy the opportunity to shorten sea lines of communication and provide critical repair parts to surface combatants engaged in near-peer combat in contested environments. In a time of fiscal constraints coupled with unreliable support provided by defense contractors, the reduced turnaround time of parts repaired utilizing 3D printing can offer increased sustainability of the CIWS found onboard DDGs. These studies provide motivation to pursue the technical skills needed within the Navy to produce critical components.

Keywords: *posturing spares, positioning spare parts, depot ship, additive manufacturing of spare parts, close-in-weapons system, CIWS, contested environment*

Background

DoD's strategic AM direction, put forth by the Joint Defense Manufacturing Council (2021) is driving towards a decentralized, downstream employment of AM throughout the spare parts supply chain, with smaller repair depots and end users primarily utilizing AM technology to produce critical repair parts. In this research, we imagine and simulate a Naval supply chain where the vast challenges regarding the implementation of AM have solutions, and AM productions sites are sources of supply similar to the role filled present day by DoD global distribution centers. Intellectual property, licensing, test and evaluation data, 3D computer-aided design (CAD) models, training of personnel, the safety of flight usage – the cavalcade of hurdles and challenges that all have been solved and put in place. In this world, when a user places an order for a part, the underlying supply system logic decides that if that part is not-in-stock, should that order be considered for printing? The primary research question in this part of the study is: how does the employment of a wide range of AM technologies impact the fulfillment of 9B cognizance code (COG) high-priority aviation consumables and affect the lead time for all 9B COG requisitions for deployed forces within the INDOPACOM area of responsibility (AOR) over a three-year time horizon? This study enhanced current tools for classifying the “printability” of individual national stock numbers (NSNs) and built a Monte-Carlo simulation based on historical fulfillment data to test assumptions about “printability” ratings based solely on an order’s continuous characteristics, then attempted to stress a fictional but possible operational AM fulfillment network (Shields, 2023).

As the distribution of power evolves across the world and creates new threats, the DoD must continually seek ways to maintain a competitive advantage among dimensions of power that enable the US to advance its interests and values. America’s competitors are becoming more assertive and technologically sound, meaning the Navy must improve readiness and adopt innovative capabilities. In the face of strategic challenges, it is important that there is a shift from legacy platforms to novel weapon system readiness. The purpose of this research was to evaluate the survivability of a primary defense weapon system onboard Arleigh Burke Class DDGs, the close-in weapon system (CIWS) under continuous operation in a contested environment based on current supply forecasting (Myles, Connell, and Loedeman, 2022). Currently, forecast supply models do not consider the increased demand in contested environments, nor additive manufacturing solution-based delivery. To extend the defense operational availability (Ao) time of primary defense systems, a selection methodology was used to identify the weapon components with the highest failure rates. Through simulation-based modeling, these components were evaluated for additive manufacturing capabilities and potential production onboard.

Findings and Conclusions

The primary recommendation offered aligns directly with current DoD AM strategic objectives. The sooner we can operationalize AM to produce safe parts while running in parallel with traditional procurement and order fulfillment methodologies, the sooner lead time improvements can be presented enterprise-wide, even when only a tiny segment of orders are fulfilled via AM. This is not a new insight. However, the results illuminate the quantitative levels of lead-time benefit potentially gained with an operationalized AM fulfillment source for naval aviation consumable repair parts and orders.

Based on our findings, there are opportunities to improve the design of our current defense supply system. Instead of carrying a surplus of critical spares, the process for determining the number of critical components should consider continuous usage in contested environments. The Navy must shift its readiness focus from dispensable legacy systems to prioritize advancement in weapon system speed and agility. Tactically and strategically, our forces must prepare to operate our current weapon systems for longer periods of time to counter adversaries in contested environments. If the Navy continues to carry current levels of spares onboard without considering continuous operations, it will limit its CIWS operation capabilities in contested environments.

Our findings also suggested that the Navy should investigate the feasibility of using AM to supply critical components on DDGs. This would increase the firing time of the CIWS and decrease the number of total spares carried onboard. Understanding that making changes to the defense budget process is complicated, analyzing spaces onboard DDGs, such as those that contain test benches, could potentially make space for new AM machines.

With the reinvention of an old idea, depot repair ships that have AM capabilities could support longer operational firing of primary weapons onboard warships in contested environments. Much like the concept that depot repair ships supported during World War I and II, using AM to posture spares can nearly eliminate logistic downtime and increase the amount of operational time at sea for DDGs and naval warships alike.

Recommendations for Further Research

This research offers numerous opportunities for future work and exploration. Several limitations within the simulation model could be areas to refine the model's parameters. For example, we could incorporate machine downtime and consider the availability of additive manufacturing (AM) machines due to scheduling work shifts and/or off-days. Other useful extensions to the simulation model would be to include into the printability heuristic cost parameters associated with engineering design time, raw materials, transportation, and operating expenses. As aforementioned, building more flexibility into the Poisson demand generator within this simulation, which can also model different demand types, such as intermittent or seasonal demand, would be a valuable addition to this effort. Refining several heuristic evaluation parameters to include more engineering-specific information on part design would add a greater level of fidelity to this model.

The most promising extension of this study is in collaborating and providing this research to the Naval Supply Systems Command (NAVSUP) Price Fighter Services and Naval Air Systems Command (NAVAIR) innovation labs for consideration and utilization into existing ongoing AM research into evaluating part and order printability. The hope is that this research informs current and future AM stakeholders to a small degree on how to best deploy, integrate, and exploit AM technology to best support the warfighter and serve the nation’s strategic objectives.

Spares modeling has only just recently begun exploring endurance logistics regarding contested environments as a weakness of the Navy’s deployed supply network. The simulations ran within this study demonstrate the effect of targeted replenishment to critical components of the close-in weapons system

(CIWS) onboard guided-missile destroyers (DDGs) and the effect that AM could produce if no logistical support existed during a heightened battle scenario. There are many factors that go into how the Navy orders, distributes, and stores these assets onboard warships, but with space and cost being the largest factors the future of expedient replenishment at sea could take many forms that the readiness-based sparing (RBS) model does not yet account for. The integration and utilization of these design and manufacturing advancements could singlehandedly change the conversation on parts constraints onboard warships and how sparing models are implemented.

Given the current state and algorithms that enable RBS systems and allow placement of spares onboard all Naval warships, a production capability at sea would ultimately change the relationship that warships in need of parts could have with the logistics network. Clean labs using stable power, distilled water, and dehumidified air would be ideal sterile conditions to continue research of high caliber AM. Recreating proven industry printing method results, but at sea, is the next step for the Navy to take to ensure AM success in ocean environments.

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NPS-22-N057-A: Expanding URL Officer Corps' Logistician Experience

Researcher(s): Bryan Hudgens, Aruna Apte, Chad Seagren, and Eva Regnier

Student Participation: LCDR Sand Miller USN, LCDR Timothy Valada USN

Project Summary

Naval leadership has identified the lack of logistics experience as a critical force vulnerability in the Unrestricted Line Officer (URL) community. The purpose of this project is to identify gaps in the knowledge of logistics matters that URL officers may possess and to develop a way to help eliminate these gaps. We find that gaps exist with respect to logistics processes and methodology at the operational and strategic levels. To begin to address these gaps, we develop a one-day course centered around practical

applications that address issues of operational availability, contracting, transportation, and facilities location. The course is designed for junior URL officers who currently attend Naval Postgraduate School (NPS) as resident students, though the course could be delivered anywhere.

Keywords: *logistics, logistician experience, unrestricted line officers, URL, education, logistics education course, logistics case studies*

Background

The Deputy Chief of Naval Operations for Installations and Logistics (OPNAV N4) has expressed concern to the Navy Surface Warfare Officer community manpower distribution (e.g., Officer Assignments, PERS-41) and the other community manpower distribution directors about the lack of logistician experience among officers in Unrestricted Line (URL) communities. This gap in logistical expertise is viewed as a critical force vulnerability to our Navy's ability to sustain prolonged operations around the globe in contested environments. The research objective is to identify important gaps in knowledge and experience for URLs in ranks O4 and above, and one or more possible ways to incorporate experience and education into URL career pathways to close these gaps.

We take the following approach for this project:

- We interview logistics subject matter experts (SMEs) to identify key concepts and knowledge that are most essential to URL officers in ranks O4 and above, to perform at the tactical and operational levels. The individuals we interview include active duty and retired officers; they span from junior to executive leadership ranks; their experience ranges from shipboard division level to OPNAV N4; and the list includes both URL officers and supply officers.
- We identify the gaps in logistics knowledge commonly found among senior officers (O4-O6) in each of the URL branches.
- We map out the typical career paths for each of the URL branches and identify the education and experience typical for current URL officers and other opportunities to increase knowledge of and experience with logistics.
- We develop recommendations for opportunities to increase logistician experience in our URL officers through education, specifically through a series of case studies, which we package into a short course we develop to educate URL officers.

We find that gaps exist with respect to process and methodology at the operational and strategic levels. To begin to address these gaps, we develop a one-day course which focuses on realistic practical applications that address issues of operational availability, contracting, transportation, and facilities location. The course is designed for junior URL officers who currently attend NPS as resident students, though the course could be delivered anywhere.

This project offers several benefits. It will inform the development of future URL leaders, for whom the Navy views their gap in logistical expertise as a critical force vulnerability. It can also inform the URL career development process, which will contribute to the manpower and personnel communities in terms of assigning officers to appropriate billets. Finally, it can inform Naval education, in terms of necessary skills and experience that the Navy must incorporate into the development of its future leaders.

Findings and Conclusions

We find that gaps exist with respect to process and methodology at the operational and strategic levels, and these gaps suggest broad areas that guide our course development. For example, URLs must understand how the logistics system may constrain or enable certain operations. Under that broad umbrella, however, logistics matters are probably more important to certain branches, i.e., submarines and special warfare, than other branches, given the national priority of their mission sets at the time of our study. Similarly, we found that some classes of supplies, such as medical supplies and ammunition, are perhaps unsurprisingly, relatively more important.

From these general areas, our analysis led to candidate topics for our course case studies, specifically issues surrounding spare parts determination, distribution in a contested environment, contracting, and sustainability are relevant for our target audience of O4 to O6 URL officers and are of sufficiently concise scope that we can address them in a classroom setting. These topics allow us to demonstrate basic analytic concepts such as operational availability and linear programming.

To begin to address these gaps, we develop a one-day course which focuses on realistic practical applications that address issues of operational availability, contracting, transportation, and facilities location. The course is designed for junior URL officers who currently attend NPS as resident students, though the course could be delivered anywhere. We suggest a trial offering for upcoming URLs, perhaps during one of the weeks between quarters.

Recommendations for Further Research

As we stated above, the purpose of this project is to identify gaps in the knowledge of core logistics concepts that URL officers may possess and to develop a way to help eliminate these gaps. We find that gaps exist with respect to logistics processes and methodology at the operational and strategic levels, and we develop a one-day course centered around practical applications the address issues of operational availability, contracting, transportation, and facilities location. The course is designed for junior URL officers who currently attend NPS as resident students, though the course could be delivered anywhere.

While the course focuses on core logistics concepts, knowledge evolves continually. Along with the "evergreen" requirement to review the course content for currency, future work could expand the course to address additional topics and/or more deeply address the topics in the current version. We also recommend the Navy consider additional short courses to include executive education opportunities for higher ranking URL officers.

References
None

NPS-22-N079-A: Secure Communication for Contested Environments

Researcher(s): Britta Hale, Jonathan Lussier, Amela Sadagic, Duane Davis, Wenschel Lan, Anne Clunan, Joseph Lukefahr, and Aurelio Monarrez

Student Participation: LT Floyd Lewis USN

Project Summary
Many current communication channels rely largely on interactive cryptographic protocols to establish security. These protocols require real-time roundtrips of synchronous interaction between devices, which makes them susceptible to channel-tear down by adversaries as well as environmental effects—subsequently leading to additional set-up time and an increased electromagnetic footprint. Within a contested environment, such protocol use presents physical vulnerabilities to logistics due to the increased location detectability from the electromagnetic footprint as well as cyber security vulnerabilities. In particular, if an adversary compromises the communications channel, they can gain long-term access to the data. This research looks at addressing this problem through use of secure asynchronous protocols. Protocols supporting asynchronicity limit downtime, offering efficiency benefits under restricted communication. They furthermore have potentially attractive security features such as self-healing security in the event of adversarial compromise of a communications channel. This research applies the Common Aviation Command & Control System (CAC2S) as a case study, framing the environment concerns to the contested restrictions anticipated under contested environments.

Several protocols are identified which offer asynchronicity and could be adopted for naval use. A few cutting-edge protocols support asynchronicity while also implementing greatly increased security features, such as Forward Security (FS) and Post Compromise Security (PCS), which may be able to protect past and future data in the event of a compromise. The Signal and Messaging Layer Security (MLS) protocols are identified as promising candidates for command and control (C2) where asynchronous support or low probability of intercept/low probability of detection (LPI/LPD) are factors. For C2 operations in a contested environment with many different systems communicating with each other, MLS presents a highly promising choice for encrypted communication protocol.

Keywords: *command and control, C2, C2 comms, secure C2, contested environment, Common Aviation Command & Control System, CAC2S, cryptographic protocols, low probability of intercept/low probability of detection, LPI/LPD*

Background

Cryptographic protocols are a critical component in securing C2 links and enabling enhanced security capabilities. While the National Institute of Standards and Technology provides standards for the cryptographic primitives in use (e.g., Advanced Encryption Standard), the cryptographic protocols that bind together such primitives vary in source from proprietary protocols to standards by other organizations. As such, the DoD currently employs a mixture of open standard and proprietary-based protocols depending on the use cases, including the Transport Layer Security (TLS) protocol used for internet connections and 802.11 used in WiFi and for some autonomous device and sensor connections. Symmetric protocols based on manual distribution of keys through use of keyfill devices are also common.

Emerging DoD requirements call for joint C2 interoperability across the cyber domain to meet National Defense Strategy (NDS) objectives as adversaries continue to develop sophisticated anti-access/area denial (A2/AD) capabilities. In fact, not only interoperability of devices but interchangeability—where one device can be used as an ad-hoc replacement for a faulty alternative to achieve mission success—have become critical. The DoD's Joint All-Domain Command and Control (JADC2) concept; the Navy's Project OVERMATCH and the chief information officer development, security, and operations task force (Weis & Geurts, 2021); and other service initiatives must effectively develop C2 technologies for this future operating environment that is called for by the NDS, this also applies to logistics (Hoehn, 2020). Consider, for example, a fleet unit that must maintain a clandestine posture where providing logistics information would be detrimental to identification by the adversary. Using an unmanned system as a relay, such information (as well as other intelligence) may be pre-loaded and sent to a separate location for C2 transmission, thus obscuring the unit's location.

The overall goal of this work is to present to relevant stakeholders a comparison of secure and sustainable solutions for mitigating emerging cybersecurity threats against C2 links and enabling secure C2 in contested environments. We frame case-study considerations under limited communication environments for the CAC2S—a US Marine Corps system for enabling C2 across multiple platforms. While the case study looks at CAC2S, the results of this work are applicable to multiple similar systems in the DoD. This research investigates both current and proposed alternatives for C2 security protocols to establish interoperability and standardization across the newly proposed Joint Force architecture. Some C2 security guarantees to consider include PCS and FS. PCS is both a newer security guarantee added to the analysis of key exchange protocols and one that has gained increasing prominence and demand in industry. It provides the ability to "lock out" an attacker after full system compromise, under certain conditions, thus allowing for advance planning against potential cyberattacks. It can even be achieved for groups of devices such as is expected under CAC2S operational contexts (Cremers et al., 2021). FS meanwhile ensures protection of data already transmitted, should such a cyberattack occur. These enhancements have the potential to harden security in any environment providing shared intelligence or other data from a known friendly platform.

Findings and Conclusions

This research confirms the applicability of recently developed C2 protocols in contested environments, and the unsuitability of traditional methods to provide security sustainability in LPI/LPD and contested environments. Encrypted C2 protocols of various types were reviewed within the context of current and emerging security concerns for communications in contested environments, as well as each protocol's ease of scalability, handling of lost messages, and recovery of communications after a connection is broken. While legacy style encryption using a single pre-agreed upon key was once thought to be nearly unbreakable, new attack methods and computer performance have changed the paradigm of encryption in the last decades, and the cybersecurity vulnerability window presented by use of such manual key changes presents a risk to logistical concerns.

Great advances have been made in the field of cryptography and cryptographic protocols, some of which enable alternatives to legacy C2 link security options. Techniques like double ratchet algorithms and Diffie–Hellman based key exchange can be used to make encrypted C2 protocols massively more resilient, secure, and able to greatly reduce data compromise in the event of a cyberattack. New and emerging protocols which take advantage of these techniques were reviewed for suitability for the Navy's use-case environment.

One notable emergent protocol, MLS, may be better suited to the Navy when multiple communication channels require C2 management. MLS provides support for message dropping and disconnection recovery, and data protection in the event of compromise via FS and PCS, meaning that an attacker who successfully guessed a key would only be able to view a few current messages before being locked out (unless they successfully inject updates to keying material at the time of compromise), and would not be able to view any past messages. A Signal connection achieves limited entity authentication after the initial handshake, whereas MLS has authentication values that support optional epoch-level entity authentication (Dowling & Hale, 2021). MLS also offers scalability to large groups and a basis as an international standard, which may benefit the Navy by facilitating ease of adoption and interoperability.

Revised or replaced alternatives to legacy command and control protections is paramount for maintaining security. Cryptographic protocols should be adopted that are resistant to tear down and adversarial attacks.

Recommendations for Further Research

For Messaging Layer Security and other similar protocol candidates, further research is required to understand the pathway and costs towards updating current systems. Research on the potential security limitations of these new protocols and possible security hardening as needed is also suggested, to not only update legacy systems to competitive security levels but look towards future improvements.

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NPS-22-N080-A: Predictive Modeling for Navy Readiness Based on Resource Investment in Supply Support and Maintenance

Researcher(s): Magdi Kamel, Kenneth Doerr, and Eddine Dahel

Student Participation: No students participated in this research project.

Project Summary

The Navy invests substantial resources to fleet maintenance in terms of part supply, corrective maintenance, maintenance availabilities, and overhauls. In order to measure and prioritize weapon systems investment decisions, an endurance supply metric (E_s) is being developed to ensure these systems are ready for tasking across the full spectrum of operations. This research project attempts to develop models to determine self-sustaining stock levels of critical parts, for key ship systems, in order to operate for at least T1 days without resupply, with a risk no greater than β1 that part shortage will cause system failure. These models are developed for both a single deployed ship and multiple deployed ships in a battlegroup. Our model shows that a small number of spare parts can significantly increase E_s for a single deployed ship operating beyond the reach of a supply chain. For multiple deployed ships, our model

suggests the desired endurance target can be reached with a limited number of additional spare parts if spare and redundant parts are pooled.

Keywords: *readiness, logistics, endurance supply, Es, Monte Carlo Simulation, MCS, reliability block diagrams, RBD*

Background

The Chief of Naval Operations (CNO) in his Navigation Plan provides his strategic vision and our Navy's four top priorities. Readiness, the ability to deliver a more-ready fleet, is an important one of these priorities. Nearly 70% of the Fleet in 2030 is already in service today. Sustaining our ships and aircraft is absolutely critical to meeting future demands. Towards this end, the Naval Supply Systems Command (NAVSUP) initiated an effort to develop a predictable supply model that ensures supply issues are not a primary cause of readiness shortfalls. A new metric called E_s or Endurance Supply is being developed to answer the question of how long the onboard inventory should be, to keep a system up and running. Traditional metrics such operational availability do not answer this question. Therefore, E_s is a measure of readiness in contested environments, without resupply.

The methodology used to guide this research is based on the Cross Industry Standard Process for Data Mining (CRISP-DM), a standard methodology and process model used to impose structure and improve success and efficiency of data science projects (Vorhies, 2016). The CRISP-DM methodology includes six phases that address the main requirements for a data science project. The six phases are undertaken in a cyclical and iterative manner and include: Business/Mission Understanding, Data Understanding, Data Preparation, Modeling, Evaluation, and Deployment.

For the modeling phase we use both Monte Carlo Simulation (MCS) and Reliability Block Diagrams (RBD) (Tobias & Trindade, 2011) to predict performance of the system as fielded. In determining self-sustaining stock levels of critical parts for key ship systems to meet Endurance supply goals, we made heavy use of known results about Order Statistics (estimation of first, second, third, etc. failures) (David & Nagaraja, 2003; Nagaraja, 2006; Réyni, 1953).

Findings and Conclusions

For a single-ship E_s, we found that endurance could be improved with additional spare parts. In a simplified model consisting of 51 more-likely-to-fail parts aka National Item Identification Numbers (NIINs), we found that an E_s target of 90 day endurance with 85% probability could not be met without additional spares. However, the addition of just 41 additional parts would achieve that target. This finding assumes that redundant parts can be cannibalized from one readiness block in the SPY-1D, to keep another readiness block operational.

For a multi-ship E_s, we modeled a battlegroup that contained 3 SPY-1D radar and found that, if the three ships did not share spare parts, the battlegroup would fall well short of the endurance target. Without pooling, 354 spare parts (118x3) were required so that all three SPY-1D lasted at least 90 days with an 85% probability, far more than the single-ship requirement of 123 (41x3). However, with pooled spares and cannibalization of redundant parts across the battlegroup, we found that the battlegroup could endure for 90 days with an 85% probability with just nine additional spare parts (123 + 9 = 132).

We calibrated our predictions against the observed mean-days-to-failure of the SPY-1D of 86 days. Based on that calibration, we predict the NIIN we model cause approximately two-thirds of failures. We further predict that without additional spare parts, the probability a system will endure more than 18 days is less than 85%. The particular sparing plan that we recommend should be cross-validated before implementation.

Our model shows that a small number of spare parts can significantly increase E_s for a single ship operating beyond the reach of a supply chain. Based on our calibrated findings, we conclude that a ship be given 41 additional spares if they will need to operate beyond the reach of a supply chain for more than the 18 days.

Sparing a battlegroup with several SPY-1D radar for endurance beyond the supply chain is more difficult, because the battlegroup's capability is degraded by the first-failure of any SPY-1D. However, if spare and redundant parts are pooled, this requirement can be substantially reduced. If pooled, our model suggests the same endurance target can be reached with as few as nine additional spares. So, we conclude a policy of pooling and cannibalizing spare and redundant parts be implemented for any battlegroup that must go beyond the reach of the supply chain for more than 18 days.

We were given the task of examining whether spare parts could help a battlegroup endure for 90 days beyond the reach of a supply chain, and if so, what level of sparing would be required. Our model predicts that, as far as system failures that are caused by part failures, this is possible.

Recommendations for Further Research

Our sparing model captures only about 68% of the causes of SPY-1D system failure. A greater percentage of failure could be captured by extending the analysis to parts that are less-likely to cause failure. But other factors such as human error and operating environment (O'Haver, Barker, Dockery, & Huffaker, 2018) also cause system failures in phased radar systems. A substantial part of the unexplained 32% of failures in the field may not be caused by part failure, at all. In sum, spare parts can help the battlegroup endure significantly longer beyond the reach of a supply chain. But other sources of failure can still prevent an endurance target from being met.

So, in addition to the cross-validation of our work, we recommend additional work be done to examine and ameliorate other sources of failure on the SPY-1D. Until that is done, while our recommendations will certainly increase endurance and the probability of endurance, they are unlikely to provide the desired risk reduction. That is, until other sources of failure are investigated and ameliorated, our recommended sparing plan will provide less than an 85% chance of enduring for 90 days beyond the reach of a supply chain.

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NPS-22-N091-A: EUCOM's POL Capability & Capacity Gaps – Single Fuel Concept Follow On

Researcher(s): Geraldo Ferrer, Eric Hahn, and Brandon Naylor

Student Participation: LCDR Rosanne Witt USN

Project Summary

This study analyzed refueling support during Phase II operations in the European theater by comparing the use of JP-5 (a kerosene-based fuel used in naval aircraft) as a single fuel against the current practice of using F-76 (a diesel-like fuel oil) for naval vessels and reserving JP-5 for aircraft. Prior studies focused on the logistical benefit provided by the Single Fuel Concept in the Pacific and on the capability gaps surrounding petroleum, oil, and lubricant (POL) distribution. We evaluated the potential costs and benefits of adopting a single fuel (JP-5) and which policy changes might be necessary to close those gaps. We modified the NPS-developed Fuel Usage Study Extended Demonstration (FUSED) model to compare the two fueling paradigms in a variety of scenarios combining pre-assault, assault, flight operations, and

sustain activities during transit between Souda Bay, Greece, and Loch Striven, Scotland. We find that the single fuel concept is the most efficient alternative, enabling greater fuel efficiency, which translates into less time spent refueling, fewer refueling operations, and less fuel consumed.

Keywords: *single fuel concept, United States European Command, USEUCOM, United States Naval Forces Europe, NAVEUR, petroleum, oil, lubricants, POL, POL supply chains, JP-5, F-76*

Background

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

The proposal to adopt JP-5 as a single fuel has raised a number of objections: (a) JP-5 contains less energy than the same volume of F-76 (a difference smaller than 3%); (b) JP-5 is usually more expensive than F-76; (c) JP-5 has lower lubricity than F-76, which may affect power plant durability; and (d) JP-5 is available in fewer ports than F-76. This study addresses the first concern, energy density. The second concern, price differential, has lost much of its relevance, considering that the prices of the two fuels have approached parity, but it deserves further study. The third concern, lubricity, has been the subject of several studies by the US Navy (e.g., Giannini et al., 2002; Guimond, 2007), and these studies indicate that JP-5 has no negative impact on naval power plants. The final concern, JP-5 availability, deserves further investigation.

In a limited inventory pooling study, Jimenez et al. (2020) found logistical benefits in the single fuel concept. In our study, we simulated realistic operational scenarios in the European theater to confirm the logistical benefits and to assess the impact of the lower energy efficiency. Our design of experiments considered three variables: battlegroup configurations, JP-5 energy efficiency, and operation duration.

- There were three battlegroup scenarios with two carrier strike groups (CSG), two amphibious ready groups (ARG), and one CSG plus 1 ARG.
- There were four levels of JP-5 energy efficiency varying from 97% to 100% of the content in F-76.
- There were nine sets of exercises, alternating seven, ten, or thirteen days of performing pre-assault, assault, flight operations, and sustain activities.

Considering the fuel consumption levels of the battlegroups in each type of exercise, FUSED was able to estimate when and where each CSG and ARG would need to replenish during their multi-day transit. The simulation with dual fuel operation was repeated four times using JP-5 as a single fuel, once for each energy content assumption. The analysis substantiated JP-5's logistical superiority.

Findings and Conclusions

Our simulations confirmed prior analysis indicating that JP-5 would provide substantial logistical benefits to operations on naval vessels. During a dual fuel operation, it is possible that the battlegroup uses up one type of fuel more than the other; the battlegroup might need to resupply F-76 while there is still JP-5 in the tanks or vice-versa. With the single fuel concept, all tanks have JP-5, and they are used uniformly for flight operations, for shipboard propulsion, or for power generation. Therefore, there is no need to replenish until all tanks have been depleted to the refueling level. This outcome confirms the results in Jimenez et al. (2020) using more complex scenarios.

Specifically, our study verified that the impact of JP-5's lower energy level was trivial. In almost all scenarios, single fuel operation required fewer replenishment at sea (RAS) events, and the combat logistics force (CLF) ships supporting the battlegroups required fewer trips to port to replenish their tanks. In some scenarios with low energy efficiency, single fuel operation required more RAS events than with equal energy content, but the additional RAS did not occur every time. Even with low energy content, it was possible to consume less fuel with the single fuel operation because the CLF ships would require fewer trips to replenish their tanks.

Considering these results, we recommend that the Navy consider switching from a dual fuel operation and instead adopting JP-5 as the single fuel in naval operations, eliminating the use of F-76. To succeed, it would be necessary to design a schedule for converting the fleet to the single fuel. The fuel tanks and the fuel lines would have to be cleaned, the CLF ships would have to be equally converted, and the supply lines would have to be established. In addition, discipline policies would have to be designed to avoid accidental contamination of JP-5 fuel tanks with F-76.

Recommendations for Further Research

Our study evaluated the logistical benefits of adopting JP-5 as the single fuel in naval operations. Switching from F-76 to JP-5 has raised several concerns (technical, financial, supply), which have been addressed in this and other studies. We found that the benefits are very significant, and that the US Navy should seriously consider the single fuel concept as the new standard for fueling its naval platforms.

Our analysis assumed a steady-state environment where all ships are ready to operate exclusively on a single fuel (JP-5), Combat Logistics Force ships are exclusively carrying JP-5, and supply points can provide JP-5 in the necessary quantities. Switching to a single fuel, however, cannot be done overnight. Fuel tanks and fuel lines must be cleaned in all ships, which would take time and money. Further research should evaluate the conversion costs and timeline, while supporting refineries should agree to gradually convert their production schedule to supply JP-5 in the necessary quantities.

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NPS-22-N140-A: Warfare Analysis of Logistics Agility in a Contested Environment

Researcher(s): Jeffrey Appleget, Marianna Jones, Jeffrey Kline, and Robert Burks

Student Participation: MAJ Mark Adams USA, LCDR Timothy Palik USN, ENS Braedon Mead USN, LTJG Edrie Orpilla USN, LCDR Matt Stymfal USN, LCDR Eddie Castellanos USN, MAJ Trevor Klemin USA, Maj Steve Warner USMC, and LT Violeta Lopez USN

Project Summary

This project conducted two distinct studies. The first (fall) study examined how maritime forces can best address casualty and medical evacuations during conflict in a contested environment set in a Western Pacific scenario. It investigated these key issues:

- What is the best mix/breakdown of supporting transport?
- How does the casualty evacuation infrastructure handle mass casualties?
- Where are the best locations for Role II medical treatment facility (MTF) placement?
- Which Role III MTFs are most utilized in the Pacific?
- How does seasonal climate impact such operations?

The second (spring) study examined the warfighting effectiveness of the expeditionary strike group (ESG) based on the mission capability of its ships as enabled by forward-deployed maintenance and repair assets.

It investigated the change in status of warships from Non–Mission Capable (NMC) to Partial–Mission Capable (PMC) in these three Western Pacific vignettes:

- What is the threshold at which an NMC ship within an ESG becomes PMC in a permissive environment in a humanitarian assistance and disaster relief (HADR) scenario?
- What is the threshold at which an NMC ship within an ESG becomes PMC in a permissive environment during patrol of an area with increasing near-peer tensions?
- What is the threshold at which an NMC ship within an ESG becomes PMC in a non-permissive contested near-peer conflict?

The insights in response to the two wargames were carefully analyzed from wargaming output and were compiled, briefed, and reported to the sponsor. Because of the sensitivity of these results, they are controlled unclassified information (CUI). The insights from the fall wargame were provided to the sponsor via the CUI Wargaming Executive Summary submitted to the sponsor in December 2021. The insights from the spring wargame were provided to the sponsor via the CUI Wargaming Executive Summary submitted to the sponsor in June 2022.

Keywords: *casualty evacuation, medical evacuation, non–mission capable, partial–mission capable*

Background

The fall study examined the Navy's casualty and medical evacuation capabilities in the following scenario:

The year is 2025, and conflict is imminent in the Northwest Pacific. The US Navy's 7th Fleet has deployed two surface action groups and two carrier strike groups to the area to accompany three Marine Expeditionary Advanced Bases. These units are the United States' and allies' first line of defense against aggression. In the event of armed conflict, casualties will be evacuated from these seven units to one of three allied hospitals, or the US Navy hospital ship.

The wargame was designed for a single team of one to three players. This team represents a United States Navy or United States Marine Corps Operational/Strategic Level Commander. The Commander is responsible for the execution of medical evacuation (MEDEVAC) transport. This game focuses on the transport of each type of casualty from the point of injury to Role III care. This system wargame has an open information format except for predictive weather that is given to the players following their random weather draw and executed by the white cell. The wargame examined three different configurations of MEDEVAC assets:

- **Configuration 1** (Hybrid) consisted of 4 expeditionary fast transports (EPFs), 4 concrete piers, 6 US-2 medical, and 6 US-2 transports.
- **Configuration 2** (EPF) consisted of 20 EPFs.
- **Configuration 3** (US-2) consisted of 10 US-2 medical and 10 US-2 transports.

Wargame design: The game is played in a sequence of turns, where each turn represents a 6-hour period. At the start of the game, the player draws a weather card that sets the weather season for the game.

Players complete the following actions each turn:

- Determine the Red Attack
- Determine the location and number of Blue Casualties
- Respond to casualties and reposition forces

Data was collected for each turn by dedicated data collectors.

The spring study's purpose was to determine the warfighting effectiveness of the ESG based on the mission capability of its ships as enabled by forward-deployed maintenance and repair assets. It investigated the change in status of warships from NMC to PMC in these three Western Pacific scenarios:

- The U.S.S. America ESG is tasked to immediately get underway from Brisbane to conduct a HADR mission in Tonga. A typhoon has struck Tonga, leaving the island in shambles.
- With tensions rising in the Pacific, the ESG has been ordered to patrol the South China Sea.
- While in the South China Sea, combat has broken out, and the ESG is targeted and suffers several casualties on most of its ships.

Wargame design: This wargame used a hybrid type with open information for the format. The board used a linear-timeline square-based design, with each block in the timeline representing one month at sea. We used individual pamphlets representing each ship, with basic capabilities listed next to a pictorial description. Player decisions were tracked through an Excel file by a single data collector after each casualty was dealt to each ship.

Findings and Conclusions

The insights in response to the two wargames were carefully analyzed from wargaming output and were compiled, briefed, and reported to the sponsor. Because of the sensitivity of these results, they are CUI. The insights from the fall wargame were provided to the sponsor via the CUI Wargaming Executive Summary submitted to the sponsor in December 2021. The insights from the spring wargame were provided to the sponsor via the CUI Wargaming Executive Summary submitted to the sponsor in June 2022.

Limitations of the fall study include the following:

- The study could only address one scenario.
- The posture mix included only manned assets.

- The care levels of interest only considered Role II and Role III MTFs.
- Homeland-theater and inter-theater medical logistics are not considered.
- The study only considered assets that will be technologically mature as of 2035.
- There is no real-world data on casualty rates produced by near-peer weapons against US ships and bases.

Limitations of the spring study include the following:

- The study was conducted in a CUI environment. A classified environment could have produced more relevant insights.
- The study only reviewed the impact on warfighting effectiveness of material condition changes in individual surface combatants.
- A classified study would have used more precise technical detail:
    - casualty specifications
    - operational taskings
    - maintenance tasks/progress

The findings both confirmed original expectations and presented areas for future research. The sponsor will use the study's results to inform a path forward for future research.

Recommendations for Further Research

Fall study: We recommend that future wargames and analytic events be conducted. We recommend workshops to better understand casualty evacuation and medical evacuation requirements in both competition and conflict phases. More studies need to be made to better understand how to stand up both Role II and Role III medical treatment facilities (MTFs), to include considering mobile Role II MTFs both with seaborne and airborne assets.

Future wargames may include the following:

1. Conducting casualty and medical evacuation wargames with players who have more appropriate backgrounds and expertise.
2. Conducting casualty and medical evacuation wargames at higher levels of classification.
3. Expanding the casualty and medical evacuation wargames to incorporate new and emerging knowledge of projected medical evacuation and casualty evacuation capabilities as well as new and emerging logistics platforms.

Because this is such a relevant topic whose findings should drive OPNAV N4 policies, we recommend that there be an annual recurring wargame that continues to examine these issues in order to inform new policy and doctrinal choices for the U.S. Department of Defense.

Spring study: We recommend future wargames and analytic events be conducted to analyze forward maintenance and repair. We recommend workshops to better understand and define Full–, Partial–, and Non–Mission Capable ratings for both surface and subsurface manned and unmanned Naval assets across the competition and conflict phases.

Future wargames may include the following:

1. Conducting forward maintenance and repair wargames with players who have appropriate backgrounds and expertise.
2. Conducting forward maintenance and repair wargames at higher levels of classification.

Because this is such a relevant topic whose findings should drive OPNAV N4 policies, we recommend that there be an annual recurring wargame that continues to examine these issues in order to inform new policy and doctrinal choices for the U.S. Department of Defense.

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N7 - Warfighting Development

NPS-22-N056-A: Interdisciplinary Study of Combating Hybrid Threats

Researcher(s): Michelle Hancock, Tahmina Karimova, Lawrence Walzer, Scott Jasper, Rebecca Lorentz, Cecilia Panella, and Chris Kremidas

Student Participation: LT Chris Mears USN

Project Summary
The study sought to answer three broad questions on hybrid threats: what are the current hybrid threat challenges; how should we respond to them; and what do we need to execute an effective response? To answer these questions, first, we analyzed the concepts of hybrid threats through the lenses of the Department of Defense (DOD) policy and doctrine, the European Union, North Atlantic Treaty Organization, and United Nations' guiding documents, as well as adversarial definitions. Second, we conceptualized an analytical framework to support designing actions to address and combat hybrid threats. Lastly, we identified key issues and capability gaps for further research.

This research employed a mixed methods social scientific approach, including qualitative and quantitative analysis to ascertain the current level of understanding of hybrid threats and to identify misunderstandings and knowledge or capability gaps. Concurrently, the research team conducted a literature review on hybrid threats and hybrid warfare to gain an understanding from the actors' point of view and to identify the actors' objectives and intentions. We also incorporated and analyzed case studies, data sets, and playbooks of historic and recent attacks to illustrate the various methods and the effectiveness of hybrid threats and to assess potential responses to these threats.

We found that adversarial powers will rely on irregular means of influence, through subversive diplomatic and military means, below the threshold of war to challenge our competitive edge across all domains, exploit vulnerabilities, and undermine the cohesiveness of national security and international partnerships. The focus of the follow-on study centers on the ongoing Russia war in Ukraine to assess U.S. framework to combat hybrid threats as well as identify effective ways for the U.S. Naval Forces, DOD, and allied partners to enhance capabilities and capacities to deter emerging threats in strategic competition.

Keywords: *hybrid threats, hybrid warfare, cyber security, cyber warfare, disinformation, misinformation, infrastructure defense, infrastructure protection, energy security, information warfare, political warfare*

Background

Our nation and allies are coming under increased attack by states and non-state actors who employ non-attributable actions below the threshold of war. These attacks weaken our competitive advantage across all domains, exploit our vulnerabilities, steal intellectual property, or undermine the cohesiveness of our alliances. These hybrid threats can be in the form of hacking networks, cyber-attacks against critical infrastructure, disinformation campaigns, electoral interference, etc. These unconventional actions cannot be answered with conventional military forces. The Chief of Naval Operations Navigation Plan 2021 states that China and Russia "have strengthened all dimensions of their military power to challenge us and our allies and partners from the seabed to space and in the information domain" (p. 2). To counter this challenge, the Navigation Plan says, "we have to do more than simply employ new capabilities—we must compete in new ways" (p. 4). The Navy's Education for Seapower Strategy 2020 addresses these "new ways" by promoting learning as a strategic advantage—we must provide "naval forces with an intellectual overmatch against our adversaries" (p. 3).

The project combined a mixed approached methodology of collecting and analyzing both qualitative and quantitative data. We also focused on a systematic exploration of each dimension of hybrid threats, assessing how they can complement each other, and how to counter these threats. The research analyzed most pertinent hybrid threats to the Department of the Navy looked at current capabilities and gaps, what approaches and means should DoN consider for combating hybrid threats effectively, as well as what methods could be incorporated into training and education curricula across the services. This research project examined past and emerging hybrid threats, challenges, strengths, and opportunities for capability improvement across maritime, cyber, Operations in the Information Environment (OIE), and Special Operations Forces (SOF) domains. First, the research team conducted comprehensive literature review and open-source intelligence analysis of interdisciplinary historical examples, case studies, as well as examination of kinetic and non-kinetic actions exercised by adversarial powers in recent years. Then, we assessed emerging hybrid threats challenges and counter-threat opportunities through examination of adversarial doctrine, strategies, policy, current tactics and operations as well as future threats in respective chapter domains (OIE, cyber, maritime, SOF). Finally, the team provided key findings and recommendations for future research.

Findings and Conclusions

The project confirmed the main hypothesis that adversarial powers will continue exercising their power through irregular means of influence, manipulation, and malign competition below the threshold of war to weaken our competitive advantage across all domains, exploit our vulnerabilities, and undermine the cohesiveness of our alliances and partnerships. The current Russian war in Ukraine provides a unique opportunity to further assess effective ways for the U.S. Naval Forces and the Department of Defense as well as the allied partners to optimize their toolkit and advance capabilities and capacities to combat adversary use of hybrid threats in strategic competition.

Key findings and recommendations of the FY22 research project highlight the following:

- OIE as a field of research and practice is about the ability to coercively impact the receiver through information appeals. It is time the field and practice of OIE moves beyond the surface examinations that typically suffice as research. Rigorous scientific methods are required to examine the data streaming out of open-source intelligence to gather an accurate read on the situation. OIE success needs interagency cooperation, education of the force, and the U.S. leading the narrative of the free societies of the world to push back against the growing influence of China and Russia in the information space.

- The assessed cyber security platforms provide adequate threat detection, enrichment, and assessment capability for a network operating in a logically isolated environment. However, there is a need for further analysis into the threat intelligence baseline used by both security orchestration, automation, and response platforms to ensure the current default settings are enabling the type of desired functionality for automated response.

- Maritime hybrid threats present unique challenges due to unclear or disputed territorial waters and exclusive economic zones, the ever-increasing density of global maritime traffic, and presence of state-owned maritime enterprises and maritime militias that can blur the lines between military, law enforcement, and civilian actors. Credible and more resilient deterrence of hybrid threats in the maritime domain should include strengthened maritime governance and cooperation with partners, training and education of U.S. and allied maritime security personnel, greater public-private cooperation, advancement of new technologies, etc.

- By focusing on systemic, technological, and organizational change, the naval SOF community can identify unique injection points into the education pipeline to enable these warfighters to be able to confront the hybrid threat environment and meet mission as laid out within strategic guidance effectively and efficiently. Simply put, intellectual overmatch in a hybrid environment is not a block to check. It is an iterative process that requires our nation to look critically at its naval force education and organization and be prepared to weaponize the SOF-peculiar cognitive edge.

Recommendations for Further Research

As the current Russia-Ukraine war continues to pose severe implications to global security, future research needs to be conducted to analyze and compare Russia's use of hybrid threats ahead of and during its war in Ukraine. As Russia continues its war, it will likely seek retribution for massive military aid to Ukraine, so our nation and allies may come under increased hybrid conflict by states and non-state actors who employ non-attributable actions below the threshold of war. Through such actions, Russia seeks to weaken our competitive advantage across all domains, exploit our vulnerabilities, and undermine the cohesiveness within our nation, as well as our alliances and partnerships.

In addition to analyzing Russia's use of hybrid threats in the current domain of conflict, future studies will assess the U.S. framework to combat hybrid threats in the areas of cyber security, information warfare, special operations, and maritime security. Additional research will be conducted to analyze best practices and lessons learned from the current war in Ukraine and identify key takeaways and findings relevant to U.S. Naval Forces and the Department of Defense.

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N8 - Integration of Capabilities & Resources

NPS-22-N068-A: Clandestine Mine Countermeasures Optimization for Autonomy and Risk Assessment

Researcher(s): Sean Kragelund, and Isaac Kaminer

Student Participation: LT Alexander Fedorovich USN

Project Summary
Mines are inexpensive, easily deployed, and put distributed maritime operations (DMO) at high-risk, particularly as Great Power Competition (GPC) requires naval forces to operate in contested environments. Autonomous underwater vehicles (AUVs) will play an increasingly important role in mine countermeasures (MCM), but research is required to optimize their performance when support from surface or airborne assets is denied or severely limited by the constraints of GPC. This project investigated methods for AUVs to conduct entirely clandestine MCM. It examined whether a conventional MCM search problem could be inverted: instead of conducting sequential operations to find and neutralize mines in a predefined transit lane, an AUV can find a navigable mine-free route that maximizes its probability of survival, potentially decreasing MCM mission timelines. Preliminary results suggest that this framework can also be used to prioritize mines for neutralization to achieve acceptable risk levels. Additional student thesis research examined methods for object detection and size determination with forward-looking sonar (FLS) to enable more efficient AUV path planning.

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

Background
Today's MCM systems still rely on surface and airborne assets for vehicle support, data analysis, and mission planning. In the contested battlespace of the future, it may not be possible to establish and maintain the permissive environment that current systems require. While AUVs are capable of clandestine operations, research is required to identify and assess new methods for conducting entirely clandestine MCM—without support from vulnerable surface assets.

Many MCM missions are search problems, and recent advances in computational optimal control have made it possible to optimize search functions performed by AUVs. Examples include area search to determine optimal track line geometry and collaborative search to detect, localize, identify, and (when necessary) neutralize mines. Past research by Kragelund et al. (2020a, 2020b) has shown that these capabilities can improve upon conventional MCM methods that rely on sequential "lawnmower" search missions to clear a designated transit lane. By using targeted rather than exhaustive search, clandestine MCM has potential to reduce MCM timelines even further. Based on prior Naval Research Program research conducted for the topic sponsor, this study topic was developed in consultation with Navy stakeholders at the sponsor's organization, the Naval Surface and Mine Warfighting Development Center Mine Warfare Division (SMWDC-MIW).

For this study, Naval Postgraduate School (NPS) researchers contacted subject matter experts to develop realistic assumptions about MCM vehicles, sensors, and operations. Contacts included topic sponsors at SMWDC-MIW, AUV operators in the expeditionary MCM and explosive ordnance disposal communities, and engineers at Naval Information Warfare Center-Pacific responsible for fielding automated target recognition algorithms on MCM AUVs. A brief literature review of search theory, optimal trajectory generation, and coordinated path following algorithms was also conducted. Finally, NPS reviewed papers by MCM planning experts at the Naval Surface Warfare Center-Panama City covering new methods for calculating and assessing MCM risk.

This study's initial focus on AUV sensing capabilities led to a thesis by Fedorovich (2022) that explored the potential to classify underwater objects using only FLS. Experiments with two different target shapes were conducted in a controlled environment to determine relationships between a target's actual size/shape and its apparent size/shape in head-on FLS imagery. Fedorovich et al. (2022) presents a potential obstacle avoidance strategy for AUVs conducting MCM in these environments.

Finally, we developed an optimal control formulation for an AUV to find a safe route through a minefield by computing a feasible trajectory which maximizes the AUV's probability of survival. This optimal control framework can be generalized to accommodate probabilistic models for mine damage, vehicle navigation, etc.; performance; and mission objectives for numeric optimization.

Findings and Conclusions

While preliminary in nature, this study found qualitatively that an optimal control framework can find a safe, navigable route through a minefield. This result relied on assumptions about an AUV's ability to detect and localize mines in the environment. These assumptions were informed by our literature review and by our thesis student's experiments with a sensor used on some actual MCM AUVs. However, additional modeling and simulation is required to assess the capabilities of actual MCM vehicle/sensor systems for clandestine MCM.

One benefit of optimal control is that it is a model-based framework. This method can generate a wealth of data for parametric studies (e.g., Kragelund et al., 2020b) by incorporating different models of the mine threat, vehicle dynamics, sensor capabilities, and mission objectives. Monte Carlo simulation can be employed to generate results for analysis. Another benefit of optimal trajectory generation is that vehicle trajectories found in this manner are feasible by definition (i.e., they can be followed by vehicle autopilots). NPS has demonstrated this on several of its autonomous vehicle systems, but rigorous experimentation with fleet MCM vehicles is needed to test this capability in the field.

In this study, we defined risk in terms of the AUV's probability of survival along its trajectory. Additional analysis is required to assess the risk to other vehicles following the first AUV's path. This risk is a function of each vehicle's navigation accuracy, acoustic/magnetic signature, etc., and was considered outside the scope of our study. However, the proposed trajectory generation framework can be modified to account for the risk to other vehicles. Alternatively, the objective function could also be modified to identify/prioritize individual mines that must be neutralized to guarantee a specified risk threshold.

In conclusion, our initial findings represent a promising approach to MCM that can be explored for future operational concepts.

Recommendations for Further Research

The preliminary results can be improved and expanded in several ways. First and foremost, a complete definition and rigorous assessment of risk is needed for clandestine mine countermeasures (MCM) operations. Methods have been developed to calculate the risk to vessels transiting through a mined area, both before and after MCM operations have been performed. Whereas these methods compute the risk to follow-on vessels transiting through a relatively large area, clandestine MCM concentrates search effort in a much smaller area to find a specific route with a much lower level of risk, provided other vessels can accurately follow it. Additional research should focus on adapting existing risk models to fit this paradigm, including the risk due to navigation errors—especially in contested environments where GPS may not be available. One way to create a common risk assessment baseline for future research is to utilize the same minefield simulation software developed by Naval Surface Warfare Center-Panama City for both concepts of operation.

Another area to explore in future research are tradeoffs associated with multiple, cooperating vehicles in contested environments. Additional simulation and analysis could help determine optimal AUV team compositions, assess tradeoffs associated with information sharing versus its attendant motion constraints, and compare mission performance metrics, among other factors.

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NPS-22-N224-A: Advancing the Application of Design of Experiments (DOE) to Synthetic Theater Operations Research Model (STORM) Data

Researcher(s): Susan Sanchez, Stephen Upton, and Mary McDonald

Student Participation: No students participated in this research project.

Project Summary

Navy leadership is interested in initiatives that can potentially increase the responsiveness of campaign analysis. Simulation-based campaign analysis is used to measure risk for investment options in how best to equip, organize, supply, maintain, train, and employ our naval forces. The Synthetic Theater Operations Research Model (STORM) is a stochastic simulation model used to support campaign analysis by the U.S. Navy, Marine Corps, and Air Force. Building, testing, running, and analyzing campaign scenarios in STORM is a complex, time-consuming process. A simulated campaign may span months, involve scores of ships and battalions, hundreds of aircraft and installations, all executing thousands of interconnected missions involving numerous events in time and space. Creating, testing, and approving the inputs for a single design point (DP) requires a significant investment in analysts' time and computing resources. Consequently, there are limits on the number of DPs that can be produced, executed, and analyzed during a study's timeframe.

This research assesses state-of-the-art methods in computational experimental design and other technologies with a goal of improving the timeliness, breadth, and robustness of future Navy studies using STORM. The long-term objectives are to apply cutting-edge sequential and adaptive design of experiment (DOE) methods in the selection of DPs to minimize the number of modeling runs required for meaningful comparisons and to develop an understanding of the conditions in which these sophisticated designs are useful in comparison to traditional baseline and excursion modeling. The DOE methods should ensure control over variation so that insights gained through analysis are meaningful, timely, and defensible. In this initial phase, we present three approaches (sequential, comparative, and focused) and describe opportunities for their use on STORM scenarios that are either unclassified, mature classified scenarios, or working scenarios. We recommend applying a mix of all three methodologies to a classified scenario in the future.

Keywords: *campaign analysis, data science, design of experiments, modeling, simulation, Synthetic Theater Operations Research Model, STORM*

Background

Navy leadership is interested in initiatives that can potentially increase the responsiveness and value of campaign analysis. One promising approach is to use recent advances in DOE for high-dimensional computational models. The Simulation Experiments & Efficient Designs (SEED) Center for Data Farming at the Naval Postgraduate School (NPS) is a leader in advancing the collaborative development and use of simulation experiments and efficient designs to provide decision makers with timely insights on complex systems and operations. This research builds on a previous partnership between the Assessment Division [N81] of the Office of the Chief of Naval Operations (OPNAV) and the SEED Center for Data Farming in exploring STORM, which resulted in four student theses (Bickel, 2014; Seymour, 2014; Cobbs, 2016; King, 2018). A suite of tools for post-processing STORM data, along with managerial approaches and controls improvements to the study process, are described in Morgan et al. (2018).

The overarching research objectives are (i) to apply DOE methods in the selection and creation of DPs to minimize the number of STORM runs required for meaningful comparisons and (ii) to determine how to best use DOE methods to complement traditional baseline and excursion modeling.

The NPS team has combined decades of experience in both the theory and application of DOE to simulation studies. This includes the use of single-stage designs such as nearly orthogonal Latin hypercubes (Cioppa & Lucas, 2007; Hernandez et al., 2012), nearly orthogonal-and-balanced designs (Vieira et al., 2013), and frequency-based designs (Sanchez & Sanchez, 2019). These are very efficient, allowing analysts to investigate the impacts of hundreds of factors on simulation responses when a brute force approach is impossible. Sequential designs (Duan et al., 2017) and adaptive sequential designs (Sanchez et al., 2010; Erickson et al., 2021) can provide further efficiencies.

Design points are the combinations of factor settings for a particular simulation run. There are two types of design points for STORM studies:

- Major DPs, such as those that reflect qualitatively different operational policies or different command and control plans, require a significant investment in developers' and analysts' time and effort. There are limits on the number of these major DPs that can be produced, executed, and analyzed during a study's timeframe.

- Minor DPs involve changes to quantitative inputs that are more straightforward to articulate and implement. For example, minor DPs might vary quantitative model inputs over specified ranges of interest. The computing effort required is often the limitation on exploring minor DPs.

Most of the SEED Center's earlier work on STORM involved minor DPs and unclassified scenarios. However, the major DPs are of most interest to OPNAV N81 because of the extensive development time and cost required.

Findings and Conclusions

We propose that different approaches be applied at different times during a STORM study process.

- A sequential approach could suggest future "major" DPs that involve inputs that are difficult to change, such as those that reflect qualitatively different operational policies or command and control plans. Determination of specific DPs to instantiate would be driven by needs/expertise/questions of N81 following deep dives into analysis and interpretation of previous major DPs. The DOE comprised of these new DPs will be very efficient (i.e., a very limited number will be created).

- A comparative approach can be used to aid in verification and validation efforts and to help identify reasonable factor ranges or levels. This involves structured parameter variation for (some of) the easier-to-change, quantitative factors and thresholds. It can provide guidance on factor ranges and combinations for which STORM does or does not produce credible output. If a working scenario is selected, comparisons can be used within the sequential approach: iterating over smaller DOEs can assist in verification/validation efforts during the (longer process of) creation of a new major DP.

- A focused approach involving one or more existing DPs could provide guidance on appropriate metrics, factor ranges or levels, or sensitivities to components or data provided by others. This does not involve creation of new major DPs. Analysis of experiments involving an existing major DP may help reveal how much variation in other DPs is worth exploring. For example, DOE could be used to efficiently identify ranges for selected inputs for which the STORM output is relatively stable, or ranges beyond which the STORM output is not credible. Other features or components to explore would be guided by general needs N81 has identified. For example, one challenge in a long-term study is the need to wait for certain types of data (perhaps coming from higher classification levels) before doing analysis. With a focused approach, we could explore what type(s) of experiments might provide useful intermediate information regarding STORM's sensitivity to components where data are uncertain or at a classification level above SECRET. These methods or lessons learned might transfer over to working scenarios, so OPNAV N81 could gain insights from experiments conducted while waiting for input from others on certain components of the STORM database.

These approaches should be applied to a classified study so we can collectively learn how best to use state-of-the-art DOE methods to complement traditional baseline and excursion modeling. Due to both COVID-related restrictions and the availability of N81 in-house STORM expertise, this project was cut short early in 2022. Follow-on research involves a classified STORM scenario.

Recommendations for Further Research

Large-scale simulation models inform many important decisions within the Department of Defense. The time required to create or modify these models often require substantial time and effort from teams of developers and analysts in close consultation with subject matter experts. Recent breakthroughs in large-scale simulation experiments have allowed analysts and decision makers to gain a much broader and deeper understanding of the model behavior while avoiding the so-called 'curse of dimensionality' that makes brute force model exploration impossible. In a nutshell, well-designed experiments consist of carefully chosen combinations of model inputs, called design points. The Naval Postgraduate School's Simulation Experiments & Efficient Designs (SEED) Center for Data Farming is a recognized leader in advancing the theory and application of large-scale simulation experiments. Data farming is a metaphor for growing data from computational experiments.

Further research is needed to address the needs of senior leaders who use models (such as campaign models) where some of the design points are difficult to instantiate. For example, some design points might reflect qualitatively different operational policies or command and control plans, and consequently have a long lead time and high cost. A better understanding of how designed experimentation can complement the traditional baseline and excursion modeling process merits further research.

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NPS-22-N252-A: Navy Expeditionary Readiness Cost Modeling

Researcher(s): Daniel Reich, and Margaret Hauser

Student Participation: MAJ Jacqueline Marshall USMC

Project Summary

According to a 2012 report from the Congressional Budget Office, military services estimate the budget for activities associated with operational readiness using mathematical models. OPNAV N834 (Expeditionary Readiness) presently uses an N81 accredited Capability Costing Model (CCM) to inform the annual sustainment requirements for the Navy Expeditionary Combat Enterprise (NECE). This research aims to analyze the CCM, execution data, and phases of the Optimized Fleet Response Plan (OFRP) to evaluate the computational and analytical performance of the model. We dissected the existing CCM, reimplemented it in the Python programming language and ran computational experiments to

compare the two implementations. We found that a lack of continuity between the model developers and those currently tasked to maintain it has led to some implementation updates that are methodologically problematic and corrected those issues in our Python implementation.

Keywords: *readiness, budget planning, capability costing model, CCM, optimized fleet response plan, OFRP, navy expeditionary combat enterprise, NECE*

Background

OPNAV N834 (Expeditionary Readiness) uses an N81 accredited cost model to inform the annual sustainment requirement for NECE (Navy Expeditionary Combat Enterprise) during the Program Objective Memorandum (POM) process. The Navy budget model is built around the Optimized Fleet Response Plan (OFRP), a structured training process used to prepare and train Navy forces for routine deployment and, if necessary, for contingency operations overseas (Congressional Budget Office, 2012). Specifically, the OFRP is a fleet force generation model that maximizes employability while preserving essential maintenance, modernization, and work-up entitlements to ensure a predictable operational and personnel tempo for forces.

Historical employment history and master execution data are combined with inflation tables to assign unit phase counts and constant year costs to each month in the time horizon. The unit phase counts and costs are input into an Excel file that utilizes Solver, an Excel add-in for solving mathematical problems, to find the "optimized" costs. The "optimized" costs are applied to future schedules or notational deployment data to forecast the total required cost for this dataset. Navy Expeditionary Combat Command (NECC) then rolls up this value into the final budget estimate.

The primary deliverable in the programming phase is the POM resource database, which can be accessed and modified in the Program Budget Information System. The POM is essentially a five-year statement of intent, and specific figures are less certain past the first two years. NECC is responsible for capturing and pricing their requirements to inform the POM build. The cost model assists NECC in calculating the optimized cost of their programs and applying it to the deployment schedule to capture the total funding requirement for the POM.

The existing model used to produce budget forecasts was developed many years ago by contractors who are no longer connected to its continued usage. Documentation on the model is not available. The model itself is implemented in Visual Basic for Applications (VBA). Our first task was to identify the mathematical characteristics of the current model and the strategy employed for solving it. To accomplish this, we dissected the VBA code to provide a formal mathematical description of the model. This allowed us to document a precise mathematical formulation of the model and identify methodological weaknesses. Our next task was then to reimplement the model in the Python programming language. In doing so, we adjusted aspects of the current implementation that we identified as problematic. We performed computational experiments on “POM23 Solver file for NCCM.xlsm”, which consisted of 678 problems.

The differences identified on 31 of those problems illustrate an opportunity for pursuing requirements-driven modeling as a future enhancement.

Findings and Conclusions

The original tool developed in VBA and using the GRG Nonlinear method in Solver ran all 678 subproblems in 3002 seconds. Our Python implementation, using Gurobi optimizer, reduced the total run time to 63 seconds, an improvement in speed of 48 times faster.

We compared the results obtained from Excel to those obtained from our Python model. We measured the difference between the objective and decision variable values for each of the 678 problems. We identified 31 problems for which significantly different solutions were obtained in the VBA and Python implementations, whereas equivalent solutions were obtained for the other 647 problems. The type of model employed, a quadratic programming approach, can produce multiple solutions with the same objective value, which was indeed what occurred in these 31 instances. Differentiating between these solutions would require additional constraints be included in the model. One approach to identifying such constraints would be to pursue requirements-driven modeling; however, to do so, both domain expertise and a modified organizational process are needed.

The decision variables are referred to as "average" or "optimized" costs. The optimized cost by job order number for the number of years based per OFRP cycle is based on the phase relationships and total cost. The models appear to be a least squares regression with constraints. Our best guess of the interpretation of the decision variables is that they represent the expected cost to have a unit in phase for a month. However, there is little evidence of a relationship between the deployment phases and the cost.

A lack of continuity between the model developers and those currently tasked to maintain it has led to some implementation updates that are methodologically problematic. When reviewing the VBA code in use, one such update we discovered was a post-processing treatment of the deployment phase cost decisions for Operations and Maintenance Navy Reserve (OMNR). The model had been allocating positive dollar amounts to deployment phase decision variables for OMNR. However, when Navy Reserves deploy, they are funded by Operations and Maintenance Navy, so this operational model would suggest that funds should not be allocated to OMNR for the deployment phase. To address this, at some point, the VBA code was updated to zero out such allocations. Within the code, though, this zeroing out was handled in post-processing rather than through the constraint system of the mathematical model itself. The unintentional effect of this post-processing was that it invalidated the intended constraint system and objective. In our modeling updates, we addressed this by implementing constraints in the model to ensure no allocations to deployment phase decision variables for OMNR. We provided instructions for correcting this issue in the existing VBA code.

Recommendations for Further Research

The cost model was originally designed with constraints presumably based on outdated assumptions that are largely unknown. The uncertainty surrounding the constraint value logic stems from a lack of documentation and discontinuity of personnel. We recommend that future studies and analyses focus on validating if the cost model design is suitable/effective. Redesign proposals must provide actionable solutions with a concrete plan to implement such a solution in incremental phases. This type of research would greatly benefit the Navy Expeditionary Combat Command cost model improvement effort. Although it is a more complex problem set, it is feasible to accomplish. It would arguably be more beneficial than simply verifying if the cost model works according to the technical specifications of an outdated original design that may no longer be operationally relevant.

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NPS-22-N260-A: Torpedo Inventory Optimization

Researcher(s): Javier Salmeron-Medrano, Jeffrey Kline, and Margaret Hauser

Student Participation: LT Violeta Lopez USN

Project Summary

Torpedo loadout decisions for anti-submarine warfare (ASW) depend on threat scenarios, capacities, capabilities of ASW platforms, and constraints on inventory and/or budget. These decisions are crucial as U.S. adversaries continue to grow their fleets and expand their global operations. Such torpedo loadout decisions are typically made in advance of the detection of an adversary submarine or even before an ASW unit is deployed. Currently, loadout plans for the Mk-54 lightweight torpedoes are made manually, and the goal of the project was to develop a decision aid, using formal mathematical optimization, for allocating ASW torpedoes in an uncertain environment.

We developed the Torpedo Allocation Stochastic Optimization Model (TASOM), which has two versions. TASOM is a mixed-integer, stochastic optimization model that seeks to minimize expected failure to meet operational goals measured by probability of kill. The optimization is subject to budget and inventory constraints, as well as other operational constraints.

Keywords: *anti-submarine warfare, ASW, torpedoes, optimal loadout, stochastic optimization*

Background

The Mk-54 torpedo type is employed by the MH-60R Seahawk helicopter, P-8 maritime patrol aircraft, and surface ships when conducting ASW operations. The “mod 0” and “mod 1” variants of the Mk-54 are currently in use. The delivery of a "mod 2" variant is expected in fiscal year 2026. Of particular interest is the procurement and allocation of mod 2 torpedoes, as they are anticipated to have significantly improved performance compared to previous variants, but at a substantially higher cost.

This trend of high-effectiveness, high-cost torpedoes underscores the need for efficient allocation of these weapons among the various platforms: helicopters, patrol aircraft and surface ships.

Given a stockpile of torpedoes, a set of weapon-delivery platforms, each with its own capacities and capabilities, and a set of possible scenarios, each of which may realize, with a certain probability, the problem is how best to allocate the stockpile of torpedoes among the platforms.

The problem addressed in this research belongs to a large family of weapon-allocation (Page, 1991; Avital, 2004; Brown and Kline, 2021), and target-assignment (Manne, 1958; Ahuja et al., 2007) problems. Our model advances the existing literature on this topic by developing analytic (vs. simulation) models, which consider multiple shooters against multiple targets in an uncertain environment.

Findings and Conclusions

Two optimization models were developed: TASOM-1 and TASOM-2. Their measures of effectiveness are combinations of torpedoes' cost and expected cost of not meeting operational goals of adversary's targets killed. The key difference between both models relates to the assessment of fire engagements that do not reach a desired probability of kill threshold. TASOM-1 minimizes the expected number of missed submarines when the consideration is binary: kill probability threshold fully met or not (in which case the target is considered safe). TASOM-2 minimizes the expected shortfall from (i.e., deviation below) the probability of kill threshold. In this case, partial credit is given to engagements that do not fully achieve the desired threshold. Both models also consider constraints on budget for: purchasing torpedoes; inventory of torpedoes already in stock; limited magazine capacity for P-8 squadrons; ships with embarked helicopter detachments; and a limited salvo size for aircraft units.

The TASOMs are stochastic. Instead of assuming perfect information regarding a specific threat scenario, which includes number of targets (adversary submarines) and identity of ASW platforms that will engage them, our stochastic models assume probabilistic information about the likelihood of several possible threat scenarios. The solution that TASOM recommends is a torpedo loadout plan that is not tailored to a deterministic threat scenario; instead, it reaches a compromise among all potential scenarios that are considered in the analysis. Thus, the solution that minimizes the total cost of (a) torpedo purchases; and (b) either expected number of missed submarines (for TASOM-1) or expected shortfall from the desired probability of kill threshold (for TASOM-2), applies to a wide range of possible threat scenarios and not just a single one. The assessed cost for not meeting a probability of kill threshold for a submarine is a planner's input.

To show the value of the stochastic programming approach over a typical deterministic planning, we present a notional case designed to represent an ASW operation where four destroyers with embarked MH-60R detachments and two P-8 squadrons are patrolling an area for adversary submarines. We assume the adversary fleet comprises 20 submarines of different classes, out of which 5 to 10 submarines are deployed. The desired probability of kill threshold is 90% for all submarine threats. One hundred threat scenarios are randomly generated where a subset of the submarine fleet deploys and appears to the patrolling ASW units. Here, we define a scenario as a configuration of deployed adversary submarines, available ASW units, and subsets of ASW units that can engage a certain submarine.

From running simulations, we observe that TASOM-1 loadout performs marginally better than the average loadout solution that can be obtained using a deterministic approach. The TASOM-2 value over manual or deterministic planning is more apparent.

Our models are combined with an accessible user interface, which facilitates generating scenarios and accessing pertinent results. TASOM uses mathematical optimization, explicitly deals with uncertain scenarios, and facilitates sensitivity analysis. Together, this research provides planners with a decision aid tool that can be used to guide torpedo allocation and budget decisions under uncertainty.

Recommendations for Further Research

We recommend further development of Torpedo Allocation Stochastic Optimization Model-2 (TASOM-2) over TASOM-1. The soft constraint used for the desired kill probability threshold is more realistic than the hard, binary, constraint in TASOM-1. Additionally, TASOM-2 solves significantly faster than TASOM-1 and has demonstrated greater performance improvements when compared to the deterministic model for the average loadout and "all-targets" loadout.

Recommended future work includes exploring the effects of penalizing the probability of kill shortfall differently. For example, an exponential penalty of degree n would incentivize spreading the probability of kill shortfall among different targets (n >1) or concentrate them on fewer targets (n <1). This would involve pre-calculating the penalty on the shortfall of a combination in an engagement.

Finally, only one test case was considered in this thesis, but additional cases should be tested to verify model results. Additional cases can be expanded to consider more realistic anti-submarine warfare (ASW) operations. In our case, all ASW units and all deployed adversary submarines were confined to one area. A more realistic case may involve ASW units patrolling their own separate areas, as in a barrier defense plan. Adversary submarines appearing in one of many areas can easily be controlled when creating scenarios. Additionally, friendly submarines, with their own, separate torpedo inventory, operating in their own, separate area, can be incorporated in a case study to represent a more comprehensive ASW operation. Multiple cases with multiple areas can be run in a series to consider a campaign-level setting.

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NPS-22-N298-A: Capturing Risk in Capital Budgeting

Researcher(s): Johnathan Mun

Student Participation: No students participated in this research project.

Project Summary

This research goal is to propose a novel, reusable, extensible, adaptable, and comprehensive advanced analytical process coupled with Integrated Risk Management to help the Department of Defense (DOD) with risk-based capital budgeting, Monte Carlo risk-simulation, predictive analytics, and stochastic optimization of acquisitions and programs portfolios. These portfolios have multiple competing stakeholders, each subject to budgetary, risk, schedule, and strategic constraints.

The research covers topics of traditional capital budgeting methodologies used in industry, including the market, cost, and income approaches, and explains how some of these traditional methods can be applied in the DOD by using DOD-centric non-economic, logistic, readiness, capabilities, and requirements variables. Stochastic portfolio optimization with dynamic simulations and efficient investment frontiers for the purposes of selecting the best combination of programs and capabilities are also addressed, as are other alternative methods such as average ranking, risk metrics, lexicographic methods, and others. The results include actionable intelligence developed from an analytically robust case study that senior leadership at the DOD may utilize to make optimal decisions.

Keywords: *capital budgeting, Monte Carlo simulation, stochastic optimization, portfolio allocation*

Background

The research applies multiple novel approaches to enhance a program's success in generating a credible and defensible return on investment (ROI) using risk-based stochastic capital budgeting techniques within the DOD. The success criteria will be to determine a defensible ROI from multiple points of view and approaches, to triangulate to a valid and reliable ROI value, and to provide guidance and intelligence to DOD decision-makers concerning the optimal program selection and portfolio allocation of resources. The analytical methods recommended in the research findings were within the constructs of a correlated portfolio of decision options that can be stochastically optimized using concepts of Markowitz efficient frontiers. Other portfolio and program selection methods such as Preference Ranking Organization Methods for Enrichment Evaluations (PROMETHEE), Elimination and Choice Expressing the Reality (ELECTRE), Multi-Criteria Analysis (MCA), and Hierarchical Scoring-Ranking (HSR) methods were also discussed.

The proposed methodologies researched include Theoretical Constructs by using a systems-dynamics approach to utilization (closed-form partial differential equation); Convolution methods to determine the frequency and quantity of use; an Analytical Framework; Empirical Impact analysis; Work-Lifecycle Total Ownership Cost with Analysis of Alternatives (cradle-to-grave lifecycle acquisitions) approach; all of which will be combined with Integrated Risk Management methodologies to run Monte Carlo simulations, advanced data analytical approaches (artificial intelligence and data science methods), strategic flexibility real options, and stochastic optimization. Economic data (total lifecycle cost, total ownership cost, acquisition cost, cost deferred, schedule, risk), logistics data (e.g., inherent availability, effective availability, mission reliability, operational dependability, mean downtime, mean maintenance time, logistics delay time, achieved availability, operational availability, mission availability, fielded capabilities, Likert levels of creative and novel technology, as well as other metrics), qualitative subject matter expert estimates (strategic value, value to society, command priorities, legal and regulatory impact scores, etc.), and market comparable metrics to operationalize various elements of DOD benefit can be used.

Findings and Conclusions

Optimizing the Navy budget requires characterization of risk in cost, schedule, and performance. This research effort conducts deep dives on risk in cost, schedule, and performance. The research goal was to propose a novel, reusable, extensible, adaptable, and comprehensive advanced analytical process and Integrated Risk Management to help the (DOD) with risk-based capital budgeting, Monte Carlo risk-simulation, predictive analytics, and stochastic optimization of acquisitions and programs portfolios with multiple competing stakeholders while subject to budgetary, risk, schedule, and strategic constraints.

The research concludes that the use of traditional capital budgeting methodologies used in industry, including the market, cost, and income approaches, might be grossly insufficient for use in the DOD. This is because traditional industry approaches rely on the concept of ROI, where there is a basis for cost and revenue. The DOD is not in the business of revenue generation, thereby negating the applicability of traditional ROI metrics. Minor modifications and adaptations would also be unsatisfactory, such as the use of cost deferred or cost savings. In such situations, the highest ROI tends to have the lowest cost or highest cost savings. From experience, we know that the cheapest and most cost-effective programs are not necessarily the best options for the DOD.

The research finds and concludes that traditional ROI methods can still be applied in the DOD by appending to these existing methods, DOD-centric non-economic, logistic, readiness, capabilities, and requirements variables. In addition, more advanced decision analytics such as stochastic portfolio optimization with dynamic simulations and efficient investment frontiers should be run for the purposes of selecting the best combination of programs and capabilities also addressed, as are other alternative methods such as average ranking, risk metrics, lexicographic methods, PROMETHEE, ELECTRE, and others. The results of such advanced analytical methods include actionable intelligence developed from an analytically robust case study that senior leadership at the DOD may utilize to make optimal decisions.

Recommendations for Further Research

Apart from purely financial and economic values, operational, logistic, and other values can be constructed and used in the prescribed modeling approaches, as investigated in the research. For instance, the use of operational and logistic metrics (inherent availability, effective availability, mission reliability, achieved availability, operational availability, mission availability, operational dependability, mean downtime, mean maintenance time, and logistic delay time) and alternative economic metrics (cost deterrence and avoidance, net present value, internal rate of return, return on investment, total ownership cost, total lifecycle cost, knowledge value added) embedded within cross-domain requirements, budgetary restrictions, as well as other strategic and capability constraints. Further analysis of the use of these metrics is recommended in any follow-on and future research.

References

None

NPS-22-N332-A: Structured and Unstructured Data Sciences and Business Intelligence for Analyzing Requirements Post Mortem

Researcher(s): Walter Kendall, Riqui Schwamm, and Ying Zhao

Student Participation: No students participated in this research project.

Project Summary

The US Navy systems may have unexpected significant cost growth for many reasons. The Office of the Chief of Naval Operations (OPNAV) manually and periodically reviews big data (structured and unstructured data) that were created within the Department of Defense requirements process to identify the programs that create excessive cost or cost growth. This research explores two questions:

1. What are the common elements of requirements that create excessive cost growth in Navy systems?

2. Assuming the elements are identified, what is the risk (likelihood and magnitude) of cost growth from common elements for both procurement and sustainment costs?

We applied classic data sciences and business intelligence tools towards a more advanced artificial general intelligence framework to analyze structured and unstructured data and identify elements and factors that create excessive cost growth. We found patterns and deep causes for high cost or cost growth programs using lexical link analysis (LLA; Zhao & Zhou, 2014), natural language processing (NLP) tools, a semantic network analyzer, anomaly detection, and causal learning concepts (Pearl, 2018; Pearl & Mackenzie, 2018). Programs with anomalous characteristics can lead to high costs or high growth. These tools provide counterfactual and drill-down discovery of the key words that explain the deep causes of cost growth. The recommendations are to apply these tools for the total benefits of analyzing Navy programs and requirements of post mortem data, towards modernizing the OPNAV's Program Budget Information System (PBIS) to become a knowledge system that can effectively learn from historical data to make better risk predictions and decisions for the future Program Objectives Memorandum (POM).

Keywords: *lexical link analysis, LLA, named entity extraction, NEE, parts of speech tagging, POS, spaCy, semantic network analysis, SNA, centrality measures, unsupervised machine learning, transformers, Program Objectives Memorandum, POM, Program Budget Information System, PBIS*

Background

Navy systems may have unexpected significant cost growth for many reasons. The US Navy's OPNAV is charged, among other responsibilities, with executing the planning, programming, budgeting, and execution (PPBE) process through a series of concurrent annual planning cycles guided by a Program Objectives Memorandum (POM), collectively referred to as POM-Year X (C. Marsh, email to author, November 4, 2022).

The objective is to leverage advanced analytics to help the OPNAV understand the common elements and causes of existing Navy systems that have significant cost growth from historical data, requirements documents, and open-source media.

The PBIS has been modernized as an authoritative knowledge system including historical data of planned and executed POM information and spending each year. Data relevant to PBIS include structured data and unstructured data. For example, structured data include number of platforms procured and procurement and sustainment costs for Navy systems. Program elements (PEs) contain PPBE information as well as unstructured data of unclassified high-level program descriptions and their elements. Initial capability documents (ICDs), key performance parameters (KPPs), or key-systems attributes (KSAs) from capability development documents (CDDs) and operational requirements documents (ORDs) are classified data sources from previous requirements processes that may have contributed to excessive cost growth. These data can be structured, such as KPPs and KSAs, and unstructured, such as PEs, ICDs, and CDDs.

We applied two categories of methods: 1. classic data sciences and business intelligence tools and 2. an artificial general intelligence framework to address the needs and research questions to analyze structured and unstructured data together and correlate them with excessive cost or cost growth of Navy systems. Specifically, we applied LLA, a semantic network analyzer, anomaly detection, and causal learning to discover patterns and deep causes that can lead to high cost or cost growth.

We analyzed two unclassified data sets provided by the topic sponsors. The first data set included seven PE documents that are processed using the LLA, artificial general intelligence NLP named entity extraction (NEE) and parts of speech (POS) tagging tools. POS features include extracted noun and verb word features. NEE features include extracted person, organization, location, product, money, event, law, language, date, time, percent, ordinal, cardinal, quantity, nationality or religious group, infrastructure, and work of art.

To discover the anomalous characteristics, we first applied LLA to compute the similarity of every two pairs of programs, then applied community finding and centrality calculation algorithms to discover the programs that are far away from community centers or on the edges of the semantic networks, which are indicators of anomalies. We used a semantic network analyzer to visualize that these Navy systems located in the center or edge of the semantic networks. The number of links are also indicators of system independences represented in the word feature networks discovered by LLA. Less linked PEs are anomalous via the unsupervised learning because they may have more unique features or innovations. We also used LLA's drill-down search capability and counterfactual reasoning of causal inferences to narrow down the key words as potential causes for the anomalous characteristics.

Findings and Conclusions

For the first data set, we found that the cost growth does not correlate with the popular, emerging, and anomalous categories of PE documents; however, some evidence shows that it may correlate with the innovativeness of the programs, which can be measured using the number of unique features of a Navy system. We also found that the numbers of people and organizations detected in the PE documents do not seem to correlate with the cost growth; however, the number of nouns (concepts) detected in the data may correlate with the cost growth.

For the second data set, we found that programs with anomalous characteristics can lead to high cost or high growth. Some anomalous PEs represented as nodes in a semantic network are less linked to other PEs and locate at the edge of the semantic network of all PEs. We also found that the number of such links computed by the unsupervised LLA are indicators of system innovations (e.g., unique features) and system independences, which are correlated with excessive cost or cost growth. We also found patterns of key words used in the PEs, i.e., key words used more than once and across multiple PEs, such as “sole source,” “recurring cost,” and “recurring engineering” can be the deep causes for the high cost or high cost growth.

The deliverables include the presentation and demonstration shown to the topic sponsors on November 4, 2022 and submission of a paper proposal to the 20th Annual Acquisition Research Symposium on May, 2023.

The recommendation for the sponsor to use the findings (e.g., semantic network independency and keywords) is to validate them with more PEs and build the knowledge into the risk assessment tools for new and future PEs.

Recommendations for Further Research

The recommendations for future work in this area are to:

- Apply the analytic tools explored in this project to the other classified data sets such as initial capability documents, key performance parameters, key-systems attributes, capability development documents, and operational requirements documents from previous requirements processes.
- Automate the planning, programming, budgeting, and execution tasks by integrating classic data sciences, business intelligence tools, and the artificial general intelligence framework and providing capabilities of index, search, link analysis, semantic network analysis, and causality analysis to process structured and unstructured data simultaneously, allowing variety of questions of decision makers answered with more ease and better explanations.
- Scale up the combined analytic tools to the Office of the Chief of Naval Operations’ Program Budget Information System (PBIS) data to predict the risk of cost growth for new and future Navy systems.
- Enable the PBIS to become a knowledge system that can effectively learn from historical data to make better assessments and decisions for the future Program Objectives Memorandum, which is consistent with the goals of the U.S. National Security Commission and industrial trends on artificial intelligence and artificial general intelligence (The National Security Commission on Artificial Intelligence, 2021; Farris, 2021).

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NPS-22-N363-A: Navy Force Structure Review Strategic Risk Workshop and Technology Review

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Project Summary
The Office of the Chief of Naval Operations (OPNAV) Lead for the 2022-2023 Navy Force Structure Review requested an interdisciplinary Naval Postgraduate School (NPS) team conduct an independent strategic risk and technical risk of the current programmed force structure and three alternatives. Three week-long efforts by thirty NPS faculty and officer scholars from various disciplines produced classified assessments and delivered them to the Navy Force Structure Review study team in narrated briefing style. This report describes the process these two risk assessments used, without providing the classified alternative force designs or results. Each assessment followed a three-phase modified Delphi process. In the first phase, participants individually reviewed alternative force design material provided by the sponsor. The second phase consisted of bringing the participants together to exchange observations. Finally, each participant individually provided assessments without further consultation. In the case of the

strategic risk assessment, the second phase included a futures generation workshop to assess alternative fleets. This process is recommended for future use in providing future fleet design strategic risk assessments.

Keywords: *strategic risk assessments, technical risk*

Background

In January of 2022 the Navy's lead for the OPNAV-wide Navy Force Review Study (NFRS) requested NPS conduct an independent strategic risk assessment and a technical risk assessment of the current programmed Navy force structure and three alternative force designs generated by the OPNAV NFRS team. The objective was to provide additional independent valuations of each fleet alternative to assist in down-selecting to one alternative for further study. A total of thirty NPS faculty and officer-scholars participated in either one or both assessments. Results were provided to the OPNAV NFRS team in two classified narrated briefings with written notes. Since these briefings are classified, pre-decisional, time-sensitive, and will be included in the OPNAV NFRS report, they are not reproduced in this report. Instead, the process used to conduct a force design strategic risk and technical assessment is recorded here for possible future applications.

Findings and Conclusions

The OPNAV NFRS team provided NPS with alternative force design descriptions for the strategic risk assessment effort. Faculty and students were recruited from diverse academic and operational backgrounds, provided the material provided by OPNAV, then came together for two one-day workshops on 11 March 2022 and on 18 March 2022 in NPS Center for Executive Education spaces to conduct the classified qualitative strategic risk assessment.

The process for this assessment used a modified scenario planning method where participants first generated a variety of possible geo-political futures with their associated likely conflicts (first workshop), then assessed each alternative fleet design in that future (second workshop). Each fleet was assessed in each future using the following metrics:

- **Robustness—**the relevance or ability of the fleet to support the United States national strategy across various futures and various national strategies
- **Resilience—**a subset of robustness, the fleet's ability to sustain damage in a particular future yet continue to operate to achieve national objectives
- **Reactivity—**the ability for a fleet to quickly capitalize on new technology advancements and react to surprise from a potential adversary
- **Recovery—**the fleet's timeliness to be repaired, rebuilt, and reconstituted during and after a conflict period.

Synthesized results of the workshops were provided to OPNAV in a classified narrated briefing format and used by a Flag level panel to assist in down-selecting to one alternative force structure for further study by the OPNAV staff.

The follow-on technical risk assessment was conducted in three phases. Select engineering and technical faculty and students were recruited to review the technical information provided on an alternative fleet design selected by the flag level panel. Participants were encouraged to make their own classified notes, observations and assessments before a group dialog. The second phase brought the participants together to hear orientation briefings on the force design alternative and to review the technical and engineering dependencies on which that force design depended. Dialog was inspired through group facilitation to exchange ideas on vulnerabilities and possible mitigation strategies. The final phase involved each participant providing a written technical assessment of the alternative force design. This process mirrored a Delphi method of bringing subject matter experts together after their initial individual rankings on a particular topic to exchange ideas, then have them re-assess their original observations individually. Individual notes, facilitation notes, and participant assessments were collected, synthesized, and provided to the OPNAV NFRS team in a classified narrated briefing.

Using alternative futures and their likely conflicts to assess a fleet design using the metrics of robustness, resilience, reactivity, and recovery is a unique application of scenario planning. This process may be used in the future to assess various fleet designs as proposed by follow-on fleet studies.

Recommendations for Further Research

The Naval Postgraduate School has a tradition of providing technical “red teaming” or providing technical risk to the engineering or employment of emerging technologies and systems. This capability is available for future system commands and fleet design developers to leverage.

References

None

N9 - Warfare Systems

NPS-22-N192-A: Bento Box—Modular/Recoverable Stratospheric Balloon Capabilities to Support Distributed Maritime Operations

Researcher(s): Wenschel Lan, and James Savattone

Student Participation: Maj Isaac Williams USMC, and LT Dylan Bonitz USN

Project Summary

In investigating the use of a modular near-space system for Distributed Maritime Operations (DMO), a notional concept of operations (CONOP) was developed to demonstrate the feasibility of a future system that can be used by Naval Special Warfare (NSW) to maximize the breadth of its resources and provide cross-platform data. This CONOP focused on a satellite communications (SATCOM)-denied environment in the Arctic, which showed that it is feasible for a high-altitude balloon (HAB) system to provide persistent overwatch and electronic reconnaissance (POWER) capabilities when existing commercial stratospheric systems are leveraged and incorporated into the mission architecture. Additionally, the reliability and robustness of this system, named the Bento Box, survived environmental testing. An ADALM-Pluto software-defined radio (SDR) was integrated with the Bento Box for this portion of the study as a bounding case for commercial-off-the-shelf (COTS) equipment that can withstand the Arctic environment. End-to-end system testing between the integrated HAB system and two PRC-152 ground user radios in a simulated ground test environment serves as a proof of concept for mesh networks with low-cost COTS equipment that are expendable but easily sustainable within a DMO construct (Williams, 2022).

Investigation of machine learning (ML) algorithms to improve overall geolocation accuracy revealed that math-based geolocation processing continues to be more accurate than ML-derived accuracy. Specifically, for maintaining positional accuracy for targets that are no longer emitting an RF signal, Kalman filtering with a chi-squared statistical anomaly detector can accurately estimate the target location. Future efforts may include exploring the use of ML during signal processing.

Keywords: *high-altitude balloons, near-space platforms, distributed maritime operations, DMO, mosaic warfare, tactical maneuvers, contested environment*

Background
Operating in hostile, contested environments is a significant concern across the Department of Defense, and the use of alternate means to maintain continuous airborne surveillance, uninterrupted communication, and accurate navigation inputs are critical to maximize the benefit of NSW forces under DMO. Guaranteed access to communication, navigation, and data transfer networks is required for successful mission execution. Unique or novel methods are needed to facilitate tactical maneuver in contested battlespaces. High-altitude balloons (HABs) offer a potential low-cost, low-observable method to increase force projection across domains and provide the infrastructure required to support NSW tactical maneuvers. Using HABs as an ad-hoc, organic asset has the potential to bring data across multiple platforms to the ground user and maximize resources in DMO.

The Bento Box, a modular HAB bus that was designed to operate independently or integrated into a host vehicle, was conceived around an educational HAB platform designed by the Naval Postgraduate School's Space Systems Academic Group (SSAG) (Gallegos, Hansen). The integration of three payloads into the Bento Box demonstrated the modularity of the structure; one such payload is a software defined radio (SDR) reconfigured as a bent-pipe communications payload to relay video transmission signals. The study concluded with a field test of the HAB-suspended Bento Box for beyond line-of-sight (BLOS) video relay between maneuver elements.

Previous research conducted by the SSAG students demonstrated that the Ettus B205mini-i SDR can be supported on the HAB bus; this included performing CONOP feasibility testing for space-to-ground, BLOS voice communication relays in very-high frequency (VHF) with PRC-152 radios for a special operations forces (SOF) use case (Swintek, 2018). For this study, the ADALM-PLUTO SDR used for BLOS video relay (Hansen, 2022) was selected as the baseline use-case scenario to explore a CONOP of an ad-hoc communications network of HABs that could optimize the space domain to support the Navy and Marine Corps' concepts of DMO and Expeditionary Advance Base Operations (EABO). The Arctic region was selected as the primary focus of the CONOP due its harsh and extreme environment, limited access to space assets, and the growing threat of Russia and the People's Republic of China (PRC) as they pursue maritime supremacy. Proven automated HAB commercial technology was considered in constructing the CONOP, along with the decision-centric mindset of Mosaic Warfare (Williams, 2022).

Modeling and simulation efforts were conducted with System Tool Kit (STK) to evaluate the suitability and feasibility of the baseline architecture centered around DMO in the Arctic environment. Incremental testing efforts, starting with bench testing in a laboratory environment, were performed to examine the cross-link functionality of two HAB systems. Environmental testing in flight-like conditions provided confidence that the current design solution will survive and operate reliably at the desired altitudes and environments that High-Altitude Balloon Persistent OverWatch and Electronic Reconnaissance.(HAB POWER) may be tasked to operate in. Lastly, proof of concept demonstrations provided valuable insight towards the feasibility of an ad-hoc near-space architecture that can support DMO for NSW (Williams, 2022).

Findings and Conclusions

This research concluded that HABs could optimize the space domain by integrating the stratosphere with the space domain and augmenting satellite-like capabilities to the tactical and operational maritime warfighter. Specifically, adapting proven automated HAB commercial technology with the decision-centric mindset of Mosaic Warfare allows for the creation of the technological concept HAB POWER. Coverage, in terms of access time over the area of interest (AOI), was the primary figure of merit in comparing the capabilities of HAB POWER and a few low-Earth orbiting (LEO), high-inclination satellite architectures in the Arctic region. This analysis highlighted that HAB POWER could provide greater persistent coverage over an AOI for a tactical or operational user. However, by integrating HAB POWER with satellites, overall space capacity and coverage is increased, creating few gaps along a maritime route's chokepoints (Williams, 2022).

Building on a balloon flight that was conducted on the Bento Box platform in June 2021, the lessons learned from this field test were applied to improve its performance. Passive thermal control was added to the bus to improve the system's reliability in extreme temperatures, both potentially on the ground and in flight. The thermal test conducted in May 2022 validated the efficacy of the thermal control design. During this test, the Bento Box was fully integrated with both an ADALM-PLUTO SDR and an LED payload to exercise the modularity features; no issues were encountered at this stage. Finally, the CONOP was replicated on the ground as a proof of concept demonstration, where bent-pipe voice communications were achieved between two PRC1-52 ground user radios that did not have line-of-sight via two fully-integrated Bento Box systems. This demonstration highlights the feasibility, given that commercial balloon technologies are utilized, of a stratospheric solution within the DMO and EABO concept. For example, a HAB POWER relay capability would relieve logistical and manning strain on warfighters that are operating distributed. Additionally, HAB POWER provides a reliable, redundant, first line of defense, satellite-like capability that augments the space domain from the stratosphere (Williams, 2022).

Investigation of machine learning (ML) algorithms to improve overall geolocation accuracy revealed that math-based geolocation processing continues to be more accurate than ML-derived accuracy. Specifically, for maintaining positional accuracy for targets that are no longer emitting a radio-frequency (RF) signal, Kalman filtering with a chi-squared statistical anomaly detector can accurately estimate the target location. However, it is understood that ML techniques can potentially improve accuracy or provide increased situational awareness of the RF signal itself when applied outside of the geolocation calculation, such as when the initial RF signal is collected.

Recommendations for Further Research

The results of this study indicate that small satellite technologies can be adapted for the stratospheric environment, and that a modular high-altitude balloon (HAB) system such as the Bento Box can act as a catalyst to operationalize the stratosphere. Therefore, it is recommended that commercial capabilities, such as commercial balloon systems and small satellite buses, be integrated together to achieve an ad-hoc mission architecture that can enhance Naval Special Warfare (NSW) capabilities in a degraded satellite communications (SATCOM) environment.

Further integration of an operational stratospheric system with existing and future satellite architectures, both military and commercial, will also enhance the Distributed Maritime Operations (DMO) concept. Especially as proliferated low-earth orbit (pLEO) constellations become available and are integrated into the Fleet, a near-space capability provides another layer of resilience in assured communications for the warfighter.

To successfully leverage machine learning for improved geolocation accuracy, further research is recommended to investigate methods for radio-frequency (RF) interference and identification, which will then have potential downstream effects on geolocation. If cloud technology can be leveraged in-situ, this will also have potential positive impacts on decision latency, both during the tasking-to-dissemination cycle and the kill chain overall.

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NPS-22-N192-B: Bipartite Graph Learning for Autonomous Task-to-Sensor Optimization

Researcher(s): Mark Karpenko, Lara Magallanes, and Ronald Proulx

Student Participation: LT Michael Zepeda USN

Project Summary

This study explores the question of how machine learning can be applied to identify the most appropriate 'sensor' for a task by optimizing task-to-sensor matching. The concept of a bipartite graph provides a mathematical framework for task-to-sensor mapping by establishing connectivity between various high-level tasks and the specific sensors and/or processes that must be invoked to fulfil those tasks and other mission requirements. The connectivity map embedded in the bipartite graph can change depending on the availability/unavailability of resources, the presence of constraints (physics, operational, sequencing), and the satisfaction of individual tasks. All these considerations may be encoded in the value matrix of the graph. Changes can also occur according to the valuation, re-assignment, and re-valuation of the perceived task benefit and how the completion of a specific task (or group of tasks) can contribute to the state of knowledge prompting the need to periodically re-solve the matching problem. The methodology for this project includes developing generic bipartite models to represent small- and large-scale task-to-sensor problems. A deep network architecture is used to understand how to solve bipartite matchings using neural networks. Network weight pruning is used to investigate strategies for accelerating learning towards online/real-time applications. The results of this study show that a deep neural network architecture can be used to solve the bipartite matching problem in an autonomous fashion. The scalability of the approach is demonstrated using an 800 by 800 graph to represent a problem scale relevant to joint targeting and fires. It is recommended that learning acceleration be further explored as part of future investigations.

Keywords: *bipartite graphs, matching problems, assignment problems, machine learning, deep learning, residual networks, large scale problems, accelerated learning*

Background

This study addresses aspects of Naval Special Warfare's question on how machine learning/artificial intelligence can enable optimization for Joint Targeting and Fires. Part of the targeting and fires problem involves the assignment or tasking of resources. This problem can be modeled using bipartite graphs. A bipartite graph has two disjoint and independent sets of vertices representing inputs and outputs (e.g., tasks [inputs] and sensors [outputs]). Each task can be connected (assigned) to a sensor by a link called an 'edge.' The bipartite graph provides an assignment when one task is connected to one sensor by an edge. The goal is to determine the set of edges that maximizes the value of the assignment, or equivalently minimizes the cost of the assignment. This is an optimization problem. Machine learning can be advantageous over conventional algorithms for solving such problems, especially in online/real-time applications, because it is possible to transform the problem statement into a differential equation. The simplicity of the calculations is amenable to hardware implementation for solving large scale problems more quickly.

In this study, deep-learning networks, specifically weighted residual networks are explored for identifying solutions to the maximum matching problem of single-layer bipartite graphs. The methodology for this project is to develop bipartite models of generic mappings for both small- and large-scale scenarios to represent task-to-sensor problems and to understand how to solve the associated bipartite matchings using neural networks. These solutions can be used by the DoD to enable autonomous link prediction in a bipartite framework. The results support machine learning enabled decision making that can be applied to the joint targeting and fires problem set.

Findings and Conclusions

Several illustrative examples of the application of the deep neural network architecture were studied. Problem sizes ranging from 4x4 to 800x800 bipartite graphs illustrated the scalability of the results. The objective of the machine learning problem is to produce (as the network output) the optimal bipartite matching. There is one output neuron for each of the possible pairings. The evolution of the neural network outputs represents that activation or strength of the connection between the input (task) and output (assigned sensor). If an output neuron has activation close to 1, then there is a connection from task i to sensor j. If an output neuron has low activation close to 0, then there is no connection between task i to sensor j. By polling the output neurons of the converged network, the bipartite graph shown can be constructed. This approach provides an autonomous mechanism for decision making. For large scale problems, it was possible to obtain solutions having similar cost values to results presented elsewhere. The sponsor should apply the approach using their specific datasets to evaluate the overall suitability of the approach for DoD problem spaces.

Learning rates are influenced by the number of non-zero network weights, as these influence the connectivity of the network layers. By applying different weight pruning templates, the convergence of the network outputs can be altered. Using one pruning template, learning was found to become destabilized, and the network output showed significant oscillations. Using another pruning template, the network outputs converged more quickly to the correct output as compared to the baseline network. This is an example of learning acceleration that can be used to improve the performance of the approach in an on-line/time-critical instantiation. As part of a follow-on study, systematic investigation of this aspect is highly recommended.

Recommendations for Further Research

This study explored the question of how machine learning can be applied to identify the most appropriate ‘sensor’ for completing a ‘task’ by optimizing a task-to-sensor matching problem. The mathematical concept of a bipartite graph provides a framework for solving this problem. Using machine learning, it is possible to transform the problem statement into a differential equation, which can be implemented efficiently to support online/real-time decision making. It is demonstrated that bipartite matching problems can be solved by using a weighted residual neural network architecture. Moreover, the approach is scalable to large dimensional problems. Accelerating the machine learning process was also studied and it was found that different constructions of the neural network weight matrix can be used to speed up learning whereas others might destabilize the learning process. Further investigation into how learning can be accelerated for online/real-time applications is highly recommended. Future work that exercises the concepts in the context of DoD specific problem data should also be done.

References

None

NPS-22-N195-B: Optimization of Business Processes through Digitization and Automation

Researcher(s): Ryan Sullivan, and Simon Veronneau

Student Participation: LT Sawyer Rogers USN, and LT William Weldin USN

Project Summary

Reporting and clerical functions at Naval Special Warfare (NSW) Echelon IV commands are ripe for digitization, automation, and optimization. While cost is a concern for prioritizing a more automated data system, there are potentially large benefits including the use of these data for prediction modelling within the Navy Sea, Air, and Land (SEAL) community. This study utilizes two unique digitalized NSW datasets to showcase how to use “big data” in the context of SEAL training and how it can be used to predict medical and performance fails during Basic Underwater Demolition/SEAL (BUD/S) training and passing various types of training evolutions (e.g., two-mile swim, four-mile run, etc.). Our main findings indicate higher probabilities for a medical fail to occur amongst males, Whites, and SEALs (both enlisted and officers). For performance fails, the results show higher probabilities for fails to occur amongst females, Blacks, Hispanics, and enlisted SEALs. Lastly, those more likely to pass evolutions are taller, older, lighter (in terms of weight), males, married, White, officers, and college educated. This study is just one example of how long-term efficiencies could be gained from greater automation of data using simple software. Some data (such as those shown in this study) could provide long-term benefit if captured in a more persistent manner. We highly advocate the implementation of a more automated data/software collection system and the use of “big data” for NSW studies going forward in the near future.

Keywords: *optimization, business process, naval special warfare, NSW*

Background
Reporting and clerical functions at Naval Special Warfare (NSW) Echelon IV commands are ripe for digitization, automation, and optimization. While cost is a concern for prioritizing a more automated data system, there are potentially large benefits including the use of these data for prediction modelling. This study shows a framework for how to use "big data" in the context of SEAL training and how it can be used to predict medical and performance fails during BUD/S and passing various types of training evolutions (e.g., two-mile swim, four-mile run, etc.). In addition, we highlight how long-term efficiencies could be gained from greater automation of data within the NSW system.

The study of adverse medical conditions related to BUD/S training is nothing new. For example, Linenger et al. (1993) analyzed medical conditions and injuries among NSW SEAL trainees and found strenuous, sustained physical training results in a high incidence of medical conditions and musculoskeletal injury in trainees. In a more recent study by Ledford et al. (2020) that examined the success of individuals in the first phase of BUD/S, the authors found that psychological and physiological resilience can be important predictors of persistence individually. Furthermore, the authors found that combining the measures provides a more holistic view to predict the success individuals in BUD/S.

This study builds on previous research and utilizes two unique digitalized NSW datasets used in a prediction model framework. The first dataset is categorized from BUD/S transcripts and includes detailed demographic information for individuals going through the BUD/S program for Naval Special Warfare. In addition, it provides the specific reason(s) for why individuals failed out of the training cycle. The BUD/S transcript dataset includes a total of 44,896 observations. The second dataset focuses on performance metrics for training under Naval Special Warfare Command. It includes demographic information as well as whether the individual(s) passed different types of evolutions (e.g., two-mile swim, four-mile run, etc.) during their training. The dataset includes a total of 106,972 observations.

For our prediction model, we use Ordinary Least Squares (OLS) in our regression analysis. The first regression model uses the BUD/S transcript data to predict being washed out of BUD/S. The second model uses the Student Performance dataset to predict whether an individual passes their evolution.

Findings and Conclusions
Our main findings indicate higher probabilities for a medical fail to occur amongst males, Whites, and SEALs (both enlisted and officers). For performance fails, the results show higher probabilities for fails to occur amongst females, Blacks, Hispanics, and enlisted SEALs. As for passing evolutions, we find that individuals who are taller, older, lighter (in terms of weight), males, married, White, officers, and college educated are more likely to pass.

This study is just one example of how long-term efficiencies could be gained from greater automation of data using simple software. Some data (such as those shown in this study) could provide long-term benefit if captured in a more persistent manner. We highly advocate the implementation of a more automated data/software collection system and the use of "big data" for NSW studies going forward in the near future.

Recommendations for Further Research

Additional research in this area should be extended toward better predicting the reasons behind medical and performance fails. Examples include examining the type of environment that contributes to injuries. Are there higher injury rates during periods of hot or cold weather? What about conditioning, persistent training, lack of sleep? While we have detailed demographic data available for this study, which we use as predictors for fails, we do not have environmental information. Developing a system to track these types of data and utilize them in a similar framework could provide useful information for decision makers within Naval Special Warfare.

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NPS-22-N222-A: Cost-Benefit Analysis of F/A-18E/F and EA-18G Simulators

Researcher(s): Judith Hermis, and Aruna Apte

Student Participation: No students participated in this research project.

This project was canceled due to the PI departing NPS, with the agreement of the topic sponsor.

NPS-22-N234-A: Networked Airborne ISR&T Long Endurance - Communications Architecture (NAILE-CA)

Researcher(s): Victor Garza, Brian Wood, Shelley Gallup, and Douglas MacKinnon

Student Participation: LT Samuel Deck USN

Project Summary

The Networked Airborne ISR&T Long Endurance - Communications Architecture (NAILE-CA) concept provides a long-haul unmanned aircraft system (UAS) sensor constellation for intelligence, surveillance, reconnaissance and targeting (ISR&T). NAILE-CA does not have network specifics to provide determination of the bandwidth, data links, apertures, compute, security, and autonomy requirements. Through analysis of current radio and networking technologies, we simulated how to optimize network traffic for the NAILE-CA concept. We found by completing a thorough analysis of sensor network traffic and correlation of data we were able to proffer recommendations on optimizing network links. These recommendations include: The NAILE concept can essentially be called a Flying Ad Hoc Network (FANET), which has a specific topology and can be modeled and analyzed. We have found that four common routing algorithms can be used to connect the unmanned aerial vehicles (UAVs) in the FANET and maintain the necessary communication links. To improve the performance of the FANET in NAILE, we recommend using a directional antenna and adding location and direction information to the routing algorithm. We also need an efficient and reliable routing algorithm that can find the best routes between the UAVs and recover quickly when a UAV is replaced due to flight endurance limitations. We have found that certain algorithms are better at building and maintaining routes quickly, according to our models. In addition, the UAVs in NAILE will need to be able to carry large payloads and have good power efficiency to extend their flight endurance. Using a directional antenna on the UAVs will help conserve power and improve the performance of the FANET in NAILE.

Keywords: *network, intelligence, surveillance, reconnaissance targeting, ISR&T, target, targeting, command and control, data link, bandwidth, autonomy, surface warfare, data management, swarm*

Background

For OPNAV N96 to determine if the NAILE-CA concept should continue in the Joint Capabilities Integration and Development System process, the communications architecture technical requirements needed to be defined.

The NAILE-CA concept is designed to use long-endurance UASs, acting autonomously as sensors, to spread out ISR over a large area, reducing the need to launch sensors from an afloat asset. This concept is designed to provide organic ISR&T of surface targets to forward units. This network constellation of UASs can accomplish ISR&T visibility with different types of sensors—including Multi-Int, Electro

Optical and InfraRed—and correlation of data afloat or ashore, or broadcast raw data to assets, so they can accomplish their own correlation of sensor data.

While the NAILE-CA concept has been advanced, issues with network communications and UAS size, weight, power and cost specifics needed to be evaluated, such as radio payloads, increased gain on antennas, increased power on radios, and reduced data rate, all to increase airborne ISR&T range.

A thesis student analyzed opportunities that were proposed for NAILE-CA applications and determined their value added in the context of surface warfare.

Examples of several airborne networking topologies have been effective in providing promising results. We reviewed previously proposed solutions, identified potential future applications, and evaluated their utility for the Navy.

Our research focused on the requirements for construction and maintenance of the links and routes between the UAV nodes in such an aerial network. We conducted a survey of previous related work and used a network model developed with the network modeling application Network Simulator 3 (NS3) as the primary means for discovering the routing requirements of NAILE networks.

Findings and Conclusions

NAILE has been proposed to provide to warfighters a persistent ISR&T capability that comes with no overhead to the units. NAILE is to be an airborne network of interconnected UAVs that collect information via various onboard sensors and then pass it to the connected customers via UAV-to-UAV multi-hop routing.

In summary, our findings suggest that:

- The NAILE concept is essentially a FANET with a more predictable and rigid topology and can be modeled appropriately and successfully.
- We found that four of the common routing algorithms that used FANETs are sufficient to build and maintain the necessary links and routes between aerial nodes.
- With the transmission distances necessary for NAILE, we recommended to use a directional antenna scheme, and to implement the addition of location and direction information into the routing algorithm route-finding packets.
- We see that NAILE will require an efficient and dependable FANET routing algorithm that can find and build network routes between nodes with the highest throughputs and must also be capable of fast recovery of broken network routes as UAVs are routinely swapped out due to

flight endurance limitations.

- We determined that some algorithms build and maintain routes more quickly than others, according to the models. With the NS3 model, it was found that all four algorithms behaved similarly with the Destination-Sequenced Distance Vector routing protocol performing slightly better than the other three due to the faster build time of initial routes.

- NAILE will require advanced UAVs that can carry large payloads. Even so, conservation of power will still be of upmost importance, since the UAV flight endurance will enable the persistence envisioned for NAILE.

- The most efficient use of power to achieve the transmission ranges necessary in NAILE will require an airborne platform-based directional antenna scheme so that NAILE may function as a directional antenna-FANET.

- The implementation of a directional medium access control configured with ready to send circular directional medium access control to broadcast packets across sequential sectors will greatly increase the transmission range of NAILE and give a more efficient use of battery power on the airborne platform.

Recommendations for Further Research

Further research is necessary to determine the realistic antenna characteristics necessary for the operational deployment of the Networked Airborne ISR&T Long Endurance (NAILE) network. This includes assessing the antenna aperture, size, weight, gain, and directivity to support the desired distances between unmanned aerial vehicle (UAV) nodes while also considering the size, weight, and power limitations of the potential UAV platforms.

Evaluation of several unmanned aircraft system (UAS) platforms have been modeled for applicability, but more research is needed to find current and upcoming UAVs that may satisfy NAILE's requirements.

A datalink mechanism is also necessary to enable nodes to find and track each other using directional antennas instead of omnidirectional broadcast.

The research conducted used the Network Simulator 3, which is a powerful tool for network simulation. However, it has limitations when it comes to modeling aerial networks with moving nodes. To more accurately model NAILE, a network simulator that allows for the removal and addition of nodes during a simulation run, and the ability to model frequencies other than the current limited ones, would be more suitable for NAILE modeling.

Additional ground to air topologies for networking UAS platforms also needs to be further evaluated for potential implementation by the sponsor.

Also, another item for consideration is determining where to complete intelligence, surveillance, reconnaissance and targeting data correlation, whether in the air, or afloat/ashore, and how that data can be safely and securely passed to ship/shore.

References
None

NPS-22-N258-A: Analysis of Pathways to Reach Net-Zero Naval Operations by 2050

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Project Summary
With the backdrop of net-zero emissions as an essential element of national security, this study undertook an analytical approach to evaluate current Department of the Navy (DON) emissions and understand energy needs to support mission readiness while reducing emissions over time. In this report, researchers present current and proposed low-carbon energy sources as possible pathways for shifting DON to net zero by 2050 with models showing four pathway options. Strategies toward net-zero emissions for the DON include alternative fuels, hydrogen, unmanned systems, batteries, improved operational efficiencies, nuclear energy, renewable energy, and carbon capture and sequestration. The research leverages existing net-zero strategies and findings developed in the public and private sectors. It identifies challenges and gaps to advance future research and analysis to further emissions reduction by the DON.

Keywords: *net-zero emissions, carbon emissions, climate change, energy security*

Background
This report is based on a broad study of strategies for the DON to achieve net-zero global emissions by 2050 to comply with recent executive orders and goals set out for the Department of Defense (DOD) and the DON. Executive Order No. 14008 (2021) calls for a government-wide approach for meeting climate-related challenges in the U.S. and set goals for agencies. Executive Order No. 14057 (2021) sets the specific goal of net-zero emissions for overall federal operations, including the DOD, by 2050 and a 65% emissions reduction by 2030.

These are challenging targets for the DOD: in 2019, DOD consumed 682 trillion BTUs, which represents up to 77% of federal government energy use. Up to three quarters of that energy use is operational; for the DON, that means ships and planes, which are two of the most difficult sectors to decarbonize. This research is critical in moving the DON toward these required goals.

With the backdrop of net-zero emissions as an essential element of national security, this study undertook an analytical approach to evaluate current DON emissions and understand energy needs to support mission readiness while reducing emissions over time. Researchers worked with the Navy Climate Change Working Group and the Climate Strategy Working Group focused on Training and Equipping for Climate Resilience to understand the current state of energy demand, sources of energy in use, and technology employed and in development for reducing emissions. Research into future demand was conducted within the context of the DON's plans for ships and planes, including unmanned systems. The team also worked with subject matter experts from other agencies and the private sector to identify and analyze the pathways under consideration in other sectors, their likelihood for success, and their relevance in the military sector.

Findings and Conclusions

Given the breadth of the topic, researchers needed to ensure the model pathways to net-zero emissions were placed into context. Because net-zero emissions are defined differently around the world and even within the DOD, identifying a clear definition was critical. Researchers relied on this definition of net-zero emissions: "a condition achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals of those same gases over a specified period" (U.S. Army, 2022). Similarly, while the report includes references to emissions-related savings at installations, the focus is on peacetime and deterrence operations.

The report presents strategies for reaching net zero, including hydrogen, unmanned systems, batteries, improved efficiencies, nuclear, renewable energy, and carbon capture and sequestration. Analysis of each strategy includes background information showing the relevancy of the strategy to emissions, advantages to using the strategy in the context of DON priorities, challenges to the strategy, and the percent of emissions reduction that may be expected over time. Key findings include the difficulties in decarbonizing ships and planes, especially when those platforms are for military use; strategies such as hydrogen, unmanned systems, and efficiencies are seeing growth and future potential.

These strategies make up four models of possible pathways to net-zero emissions. The four models are sand charts that show the role that each strategy will have in four scenarios: (1) baseline or status quo; (2) pushing technology and operations; (3) aggressive advances; and (4) aspirational and aggressive advances.

This report contributes possible solutions to the complex challenges facing the DON, DOD, U.S. government, and the country as a whole as emission reduction strategies are considered and executed. The work will inform current efforts within N94 as it maps future energy demand and strategies for emissions reduction and within the DON, including the Navy Climate Change Working Group and working groups under the Navy Climate Strategy. These concepts, over time, can also benefit the DOD through incorporation into the National Defense Strategy and by informing metrics and actionable goals to support reductions in emissions or carbon emission credit programs.

Recommendations for Further Research

Researchers found significant gaps in data and information relevant to reaching net-zero emissions by 2050. Due to these gaps, researchers had to make certain assumptions to calculate potential emissions savings. Given this, the pathway models could benefit from improved underlying data for: additional operational efficiencies in ships and planes, advances in low-carbon fuels, ability of hydrogen-based systems to scale up, emissions savings from the use of unmanned systems, battery storage capabilities, operational use of renewable energy, and carbon capture and sequestration, especially in submerged lands of naval installations.

Research is ongoing in these areas, and as the report's models reflect, data for each strategy can be updated to recalculate revised sand charts and identify future pathways to net-zero emissions. This would allow recalculations based on advances in one or more energy sources or a new technology introduced into DON operations.

Working with the topic sponsor, research is underway on a year two Naval Research Program project entitled *Advancing Pathways to Net Zero for the Operational Navy*. This research builds on the current report to move from pathway identification to prioritization and operationalization. The team will develop requirements for priority pathways to identify ways to operationalize them by researching the following questions: What are the most significant challenges for reaching net-zero emissions for the operational Navy? What are the requirements needed to operationalize the pathways to meet mission and reduce emissions?

These findings will contribute to the interdisciplinary work underway within the DON and DOD as the community makes strides to reach net-zero emissions by 2050.

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NPS-22-N265-A: Electrical Energy Storage Strategy to Support Electrification of the Fleet

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Project Summary

Lithium-ion (Li-ion) batteries have begun to proliferate across the U.S. Navy fleet, commercial shipping, and in many other naval contexts. Naval engineers must account for Li-ion batteries when designing new vessels to ensure safety and adequate integration of the batteries into ship electrical systems. This research examines current Li-ion battery use and predicts battery requirements for the U.S. Navy's operating force in 2035 and 2045 from a mission engineering perspective and surveys key topics, including battery chemistry, energy density, charge/discharge rate and safety concerns. Projections of future battery requirements for the operating force in 2035 and 2045 are developed, highlighting the likelihood that several classes of ships will have significant growth in Li-ion batteries stored aboard in the future fleet. The role of Li-ion batteries, however, will likely be limited to running specific subsystems or equipment and will not replace ship generators. This limitation will remain true until the energy density of battery technology can compete with petrochemicals, a capability which, if even possible, is many years away. Finally, a software tool, developed in Microsoft Excel, is presented to aid in the prediction of future Li-ion storage requirements in the fleet.

Keywords: *lithium, lithium-ion batteries, li-ion, energy storage, electrification of the fleet, directed-energy weapon, DEW, high-energy laser, HEL, hybrid electric drive, HED*

Background

The design, development, and fielding of new and emerging technologies onto Navy vessels is driving an increase in power requirements. The Deputy Chief of Naval Operations Warfare Systems (N9) office requires research be conducted to assess the current employment of lithium-ion batteries within the fleet and to aid in determining future battery requirements to power a wide variety of vehicles, weapons, and other systems. To achieve this objective, five systems engineering capstone students augmented the efforts of three department faculty members to conduct the research. Li-ion technology has quickly become the power source of choice for systems that have large, instantaneous and/or continuous power needs, and the Navy currently expects that Li-ion battery technology will continue to be needed to support many future systems. This research is intended to inform the Department of the Navy of the current state of Li-ion battery use and to substantiate requests to secure more resources to appropriately equip the fleet through 2045.

The focus of this study is battery technology aboard major U.S. Navy surface combatant ships. Small Navy vessels, submarines, supply and transport ships are not included in this study, despite potential for a Li-ion footprint. The team searched open-source and unclassified government publications, journal articles, news articles, publicly available product specifications, and other online sources. These sources were, however, somewhat limited, due to the sensitive nature of many systems currently using Li-ion battery technology.

To assess the current use of batteries in the fleet, and to predict the future growth of battery use to inform future ship construction and systems integration planning, the authors divided the effort into four parts. First, the authors identified Li-ion battery systems currently used in the fleet and key aspects of their implementation, including the location of the batteries and any available specifications, such as capacity, voltage, and intended use. Second, the team attempted to predict future battery use in both the mid-term (2030) and far-term (2045). This included considering vehicles and subsystems that are not currently battery powered but could be within these timeframes, based on predicted future Navy force structure; thus, the combination of the systems that could use batteries and the total number of systems provided a basis for the prediction of battery use in the future Navy. Third, the team considered the tradeoffs between energy generation and storage based on the requirements derived from the future fleet structure, highlighting the strengths and weaknesses of both. Finally, the team assessed future battery use across the fleet in the mid and far term, based on the future fleet structure and the trade space analysis, and presented a software tool to aid future research.

Findings and Conclusions

The research supported the original assumption that Li-ion battery technology will play an increasing role in the electrification of the fleet. The energy density of Li-ion batteries, in contrast to petrochemicals, is a long way from serious consideration as an option for ship propulsion; however, there is a significant role for Li-ion in powering mission-related systems and vehicles from a host vessel. The key challenge with estimating the exact quantity of Li-ion batteries that must be stored on future platforms is the unknown rate of Li-ion technology growth. Li-ion has experienced exponential growth in both general prevalence and improvement to its energy density since 2008, but it is expected that this growth will plateau at some point in the relatively near future.

Key considerations for shipboard Li-ion battery integration include the risks associated with thermal runaway and fire. For years, many small, unaccounted Li-ion batteries, such as those used for personal mobile phones, laptop computers, and battery backups for small electronics have been carried aboard Navy ships, while other Li-ion batteries, such as those used in missiles and sonobuoys, have been subjected to formal review processes even though they may be smaller or less of a fire risk. Loss of life or ship due to an uncontrolled thermal runaway is likely the greatest risk posed by Li-ion batteries; however, it is unrealistic and unnecessary for the Navy to monitor and control every Li-ion battery that finds its way aboard a naval vessel. Consideration should be given to the battery's intended use and storage location, including its proximity to critical systems.

Li-ion is here to stay, and continued investment in Li-ion battery technology will, among other things, support the improvement of its energy density—thereby making Li-ion batteries even more applicable for future integration use cases. Continued investment in fire suppression, packaging and handling processes will help the Navy integrate the latest battery technology while minimizing risk to platforms and sailors. Perhaps most importantly, careful planning must be undertaken in future ship designs to account for the space (and other logistic) requirements borne of the ever-increasing demand for lithium-based energy storage. The use of specially-tailored software tools, such as the one provided in this study, may aid in the effectiveness of future designs and deliberate risk planning efforts, and should be regularly updated with the most current data to maximize the tool's utility.

Recommendations for Further Research

Although the lithium-ion (Li-ion) battery shipboard integration estimation tool developed in Microsoft Excel in support of this research effort sufficiently organized the available data, updated data collected from subject matter experts in the specific technologies using lithium-ion batteries for naval applications should be inputted before the results are used to inform any major integration decisions. This study used available open-source data, but more accurate or current data may alter the trends presented in the summary. As was suggested in the final report, there are many other software packages that could be used to build a similar tool, including better database-management options such as Microsoft Access, Structured Query Language, or Mongo Database, even following the same design; however, most anticipated users are unlikely to be familiar with or have access to these databases software tools, hence the choice to use Microsoft Excel.

The team is aware of some previous efforts to capture Li-ion use in the fleet. It is recommended that future efforts capture the data elements necessary to populate this tool, as the incorporated metrics are the most salient for informing decisions regarding the implementation and adoption of Li-ion batteries when considering the risks to a particular ship. The team also recommends that the tool be extended to account for individual ships via another lookup table to delegate the platform-to-ship association to each ship's commander. Any ship may contain different platforms based on an assigned mission, so its Li-ion energy storage may vary by mission in addition to varying by the timeframe. If successful in implementation at the ship level, the Navy may consider implementing tools based on storage or use-location onboard a ship.

Understanding the general number and capacity of Li-ion batteries onboard a ship is a good starting point, but the fire risk also associated with their proximity to one another—aggregate storage—is also a very significant factor. Naval engineers should understand the risks associated with Li-ion battery storage and how those risks may affect future designs; however, legacy ship designs will remain prevalent in the modern Navy and must be considered. Likewise, future platforms will be brought onboard ships that were not initially designed to carry/service them. Basic inventory-like tracking of Li-ion batteries onboard ships using a tool such as the one presented may be helpful in platform-based risk assessments, as well as informing broad Naval policies.

References

None

NPS-22-N275-A: Using Additive Processing to Harness and Implement Graphene Technology for Wear and Corrosion Protection

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Project Summary

Graphene is an amazing two-dimensional material that has garnered much attention since it was first fabricated nearly 20 years ago. Since its discovery in 2006, scientists and engineers have attempted to find applications of graphene, both standalone and as part of a composite material, to bring the nanomaterial to market. As of 2022, nearly 20 different products have come to market taking advantage of one or more of graphene's amazing properties, e.g., use as a flexible touch screen for smartphones due to its high electrical conductivity, stiffness, and optimal optical properties. This study focused on using graphene in both a polymer matrix composite and in an aluminum cold-sprayed coating. Graphene was added to a common polymer, polyethylene terephthalate glycol (PETG), to improve its hardness, wear resistance, and ultraviolet (UV) resistance. The nanomaterial improved the hardness and wear resistance but experienced greater degradation when exposed to UV-B radiation at high temperature and humidity. Graphene was also added to aluminum (Al) powders, which were then cold sprayed onto an aluminum substrate. The graphene improved the hardness and adhesion strength of the coating but saw reduced wear resistance. Both effects were attributed to the interaction of the graphene with the Al "splats" in the coating. Improvements to wear resistance was observed in PETG but not in the Al composite coating. The Al composite coating exhibited small improvement in adhesion strength and hardness. Increasing the amount of graphene in these composites may further improve the mechanical properties of the composite materials.

Keywords: *graphene, additive manufacturing*

Background

The overall objective of this study was to analyze the potential of graphene-based materials, like graphene nanoplatelets (GNP), for use in naval applications. Of specific interest was the use of GNP in protective coatings for ship hulls, fuel tanks, or other parts that are exposed to severe wear and corrosion damage. If graphene can enhance resistance to wear and corrosion, while minimally or even positively impacting cost, then the technology could be ripe for transition to the fleet. Of the several specific research objectives, the first was to investigate any environmental concerns to marine life or health implications of using graphene-infused material. The second objective was to study the cost-benefit of adding graphene to materials and the marketability of these composites. The third objective was to validate the incorporation of GNP to additive manufacturing processes like fused deposition modeling or cold spraying. A fourth objective was to analyze any changes to the microstructure and mechanical properties of graphene-infused coatings or 3D-printed polymer parts and whether the GNP enhance resistance to wear and/or corrosion.

A literature review was conducted to investigate possible toxicity and cytotoxicity of graphene-based materials like GNP. The scope of this review included graphene released to waterways and the soil and any possible effects. Another review of case studies of the cost-benefit of adding graphene to products brought to market was conducted. For objectives three and four, a polymer, PETG, and a metal coating, Al, were chosen. PETG pellets were mixed with GNP (no more than 1 vol%) in a Felfil filament extruder. Composite filament was then used to print 5 cm x 5 cm x 3 mm samples. For Al, GNP (this time 2 vol%) were mixed with Al powder using a high energy ball miller. The composite powders were then cold sprayed onto an Al-6061 substrate. After the substrates were sprayed, they were heat-treated at 400 °C for 20 minutes in an inert argon atmosphere.

Once printed, polymer samples were wear tested in a Nanovea T50 tribometer using 3 mm stainless steel balls to wear down the surface. Three one-hour wear tests were performed on each sample. Once complete, the PETG and PETG-GNP samples were examined in a scanning electron microscope (SEM). Cold-sprayed Al and Al-GNP samples were also wear tested with similar parameters to the polymer samples. The metal samples also underwent micro- and nano-indentation testing and adhesion strength testing. Adhesion testing left a fracture surface in each sample. The fracture surface and a cross-section of the fracture surface from each sample was investigated with both an optical microscope and a SEM.

Findings and Conclusions

There are several ways for graphene to enter the environment. The most likely avenues are application of graphene as an absorbent for cleaning fluids of metals and molecules. The graphene would be released and contribute to cleaning a waterway, for example. Removal of the graphene, however, would be difficult. Graphene could also enter soils and, subsequently, waterways. When in the soil, the graphene may interact with the nutrients and chemicals, changing the pH and affecting the soil ecology. Research in this topic is still nascent, and the extent of the effects of graphene and its derivatives in the environment is yet undetermined.

The small addition of GNP to PETG greatly reduced the transparency of the polymer, which was received as clear filament from the manufacturer. Some of the samples were then exposed to UV-B radiation at higher temperatures and humidity to accelerate the polymer's aging. The polymer microstructure was examined, and samples were wear-tested. The composite polymers exhibited higher wear resistance before accelerated ageing. Wear width was smaller and wear depth shallower in the PETG-GNP sample compared to the PETG sample. This was reversed with the samples exposed to UV/heat/humidity. The composite had a wear track 35% wider and 25% deeper than the exposed PETG sample.

For the Al-GNP system, the composite coating showed lower porosity; however, the coating was thinner compared to the control Al coating. The cause was likely due to clogging of the cold spray nozzle. When spraying with the composite powders, the nozzle would clog due to GNP depositing on the interior surface of the nozzle. The micro-indentation hardness of the Al-GNP was 75% higher than the pure Al coating, while the difference in nano-hardness and elastic modulus were negligible. The Al-GNP also had smaller variance in nanoindentation tests. Plasticity was indistinguishable for the two coatings. The micro-indenter creates a larger indent with a larger load of the surface, increasing the chances of indenting splats with attached GNP. The chances of this happening with the nano-indenter were low in comparison. The nano-indenter hit a larger proportion of bare matrix material, measuring values closer to that of the Al. The wear loss in the GNP sample was 300% higher than the loss found in the Al coating. Further, the wear depth was 50% deeper. Despite the improvements in the hardness, the decrease in wear resistance of the composite coating is also due to the GNP's presence. Because of the bridging of splats by the GNP, when a splat comes loose from the bulk, it brings along a single graphene platelet. So, instead of lubricating the surface as graphene normally does in cases of frictional relief, the splat/GNP combination contributes to wear of the surface.

Recommendations for Further Research

Despite these mixed results, the amount of graphene nanoplatelets (GNP) in both composites were low and, unlike carbon nanotubes, GNP are easier to disperse during mixing. So, a higher concentration of GNP should be possible and may lead to greater improvements in mechanical properties. Further research should focus on increasing the amount of GNP introduced into the composite while also ensuring good dispersion of the nanoparticles. Although aluminum was considered as the metallic matrix composite coating in this study, other sprayed metals like copper or its alloys may benefit from the addition of GNP in terms of wear and corrosion resistance.

References

None

NPS-22-N278-A: Expanding Rigid Hull Inflatable Boats (RHIBs) Survivability via Cost-effective Up-armoring

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Student Participation: LT Patrick Tapp USN

Project Summary
Small boat crews operating rigid hull inflatable boats (RHIBs) during maritime interdiction operations (MIO) are left exposed to adversaries' hostile actions. In conducting visit, board, search, and seizure (VBSS) and other close in surface actions, boarding teams are prone to gunfire from above, or directly on the beam, placing them and their small craft at significant risk. While the RHIB is well known for being swift, lightweight, highly maneuverable, and multifunctional, it suffers from an unshielded distant approach, a need for demanding boat handling skills, and assumes generally inferior positioning and full exposure while lying alongside larger vessels. To reduce the potential for crew casualties and increase RHIB critical component survivability without negatively impacting operational mission success, a cost-effective, lightweight, unencumbering, and easily installable retrofit is needed. This study investigates the function of critical components and systems, appropriate material solutions to protect the prioritized elements against small arms, and blast fragmentation effects, while not deterring from the vessel's mission capabilities. Additionally, impacts on buoyancy, stability and other ship's performance characteristics are studied to inform a suitable solution set for RHIB enhanced survivability.

Keywords: *rigid hull inflatable boat, RHIB, survivability, shielding, composite materials, up-armoring, maritime interdiction operations, MIO, visit, board, search, seizure, VBSS, space weight and power, SWaP*

Background
A highly versatile waterborne craft, the RHIB serves as the primary mode of transportation for VBSS teams conducting MIO. It is lightweight, maneuverable, and gives operators direct access to their surroundings. However, these same characteristics place the RHIB and its crewmembers in a vulnerable position. Coming alongside a suspected hostile vessel, typically having the height of eye advantage, exposes the RHIB from above and at close range abroad. The crew, riders, engines, control systems, and structure are all potential targets for gunfire cascading down and inflicting casualties. Operationally, this last mile, the transfer of combat operators to suspect vessels, is required to conduct the mission. Thus, a material solution must be investigated to resolve this threat to mission failure and loss of equipment and Sailors.

Past military systems have benefited from postproduction changes in design to suit operational needs. The High Mobility Multipurpose Wheeled Vehicle (HMMWV), better known as the Humvee, is an example of this. After seeing higher-than-expected losses due to due to heavier caliber gunfire in the field, Improvised

Explosive Devices (IED), and landmines, Up-Armored HMMWV (UAH) kits and other self-protection enhancements were retrofitted to the M1114 HMMWV. The UAH consists of armor protection, which includes welded aluminum, composite, and steel plates, as well as reinforced glass panels which provide the Humvee occupants with enhanced ballistics protection against fragmentation and direct blast overpressure. However effective, these increases in survivability come at a significant cost in terms of overall vehicle weight. This is an area of particular concern in ships and small craft as changes in the center of gravity and mass distribution directly impact power, stability, and maneuverability, not only in the subject RHIB, but also in the ship deploying this asset.

The RHIB is typically deployed via a boat handling system that is an integrated subsystem of the ship. Additionally, the RHIB serves many functions within the ship system, being utilized for search and rescue, resupply, liberty launch, and even, perhaps, as the captain's gig. Thus, mission performance in a combat scenario must also be weighed against all other uses. Limiting the intrusions that survivability enhancements typically bring is a key factor in the successful implementation of a potential material solution. In order to come to a viable outcome, operational, technical, and programmatic input was necessary to ensure the mission-critical functions were not compromised.

For this study, the following methodology was used. A representative RHIB variant, the 11m boat, was selected. Critical mission components and key characteristics were assessed for survivability in two cases, namely a top-down scenario and one at a broadside. Threat analysis was conducted using typical small arms and anti-personnel explosive devices in order to examine mechanical failure through impact, holing, and blast overpressure. Protection requirements were compared with the known material properties of the existing components. In the cases where material deficiencies were identified, parametric analysis was conducted to determine design solution modifications that increased strength or stopping power against the unwanted impacts of added weight, reduced stability, and interoperability considerations.

Findings and Conclusions

Cost-effective up-armoring of the RHIB will enable it to continue as the small craft workhorse of the fleet for years to come. To this point, lightweight-weight ballistic protection and armor-piercing resistive shielding materials and coating systems were investigated. Minimization of additional weight and bulk thickness as compared to failure strength and kinetic energy dissipation were viewed as primary attributes. Optimization of mobility and field of view is also highly desirable as inherent properties of a recommended solution.

Through the study of various threat cases, it was found that survivability enhancement of the RHIB could be enacted under certain conditions. Readily available explosive devices such as hand grenades, which pose multi-dimensional failure mechanisms, were found to be difficult to provide acceptable technical solutions against, while the small arms cases were more readily obtainable.

It was concluded through engineering analyses and system design studies that through the use of material characteristics changes such as an increase of thickness in the normal direction, small arms fire could be defeated, or adverse effects minimized to acceptable levels. Tradeoffs in stronger materials were considered to mitigate form factor interference and performance degradation at the expense of weight density. While the updated armor systems considered provide enhanced stopping power as measured through a reduction in residual bullet velocity, the additional weight considerations still preclude the liberal use of this solution to limit the puncture or holing of all decks, collars, and other key components. Additionally, it was determined that force protection of personnel was adequate using the currently available options to operators within the standard fleet practice.

Recommendations for Further Research

While the use of computer modeling and simulation in support of the analytical analyses performed herein provides insight into the survivability enhancement recommendations necessary for the Rigid Hull Inflatable Boat (RHIB) against the representative threats that were studied, it is recommended that these technical solutions be tested at sea with operators' input to fully assess any impacts on operational mission capabilities. Furthermore, potential adverse effects introduced into the larger ship system through changes to the RHIB must be verified via field testing while being operated at sea. Detailed study of changes to the center of gravity, righting arm, and stability curves through the addition of topside mass are suggested, as are additional studies regarding launch and recovery performance as a result of selected material modifications. Additionally, the operational impacts on the cost to the fleet in modifying the RHIB and/or providing piecemeal up-armoring solutions (kits) should also be examined in greater detail to understand the benefits given constrained resources.

In the course of study for this problem, it was discovered that additional investigation of composite materials used in marine craft is necessary. While engineering data in ballistics and blast is readily available for traditional metals, less is known regarding the failure of the lightweight, flexible, and multi-scale materials being utilized in the RHIB and autonomous unmanned vessels entering the fleet. Specifically, it is recommended that blast and impact effects against composites are studied further.

References

None

NPS-22-N304-A: Operationalizing Naval Special Warfare for Countering Weapons of Mass Destruction

Researcher(s): Eugene Paulo

Student Participation: LCDR Joseph Grim USN, Christy Spaulding USN, Ryan Cervino USN, and Allen Zahneigh USN

Project Summary
The joint force's ability to detect chemical, biological, radiological, nuclear, and explosive (CBRNE) anomalies in an expeditionary environment is challenging. Small navy special warfare (NSW) and explosive ordnance disposal (EOD) units perform disaggregated maritime reconnaissance operations to surveil spaces, but they lack flexible CBRNE detection and reporting capabilities. Because of the nature of CBRNE hazards, a man-portable unmanned aerial vehicle (UAV) approach is required to prevent the spread of contamination, ensure the safety of small tactical units, and maintain stealth in a combat environment. Using an iterative, model-based systems engineering (MBSE) process, the proposed chemical/biological agent nuclear and radiological yield (CANARY) system of systems (SoS) combines an aerial vehicle, a CBRNE sensor, and a link 16 communication system to confirm or deny CBRNE presence and relay information for follow-on retrieval, containment, direct assault, or joint fires support. The CANARY SoS was designed for man-machine teaming to transform operational needs into a description of system performance parameters and a system configuration. This design was used to identify and screen three candidate UAVs: the SkyDio, SkyRaider, and NOVA 2. A realistic, operational scenario shows the CANARY SoS deployed in an austere expeditionary environment. The ground control operator deploys CANARY to survey the site for CBRNE material/agents, create aerial video footage, and transmit the encrypted mission data. Simulation was performed to evaluate which performance characteristics have the greatest impact on system effectiveness. Measures of effectiveness (MOEs) include the time in which the system can detect, analyze, and confirm the presence of a threat, and the percentage of threats successfully confirmed. Of the three candidates, the program of record (POR) SkyRaider was superior regarding defined CANARY SoS requirements, including UAV speed and battery life. The non-program of record candidate, the NOVA 2, is recognized for its ability to perform within confined space environments.

Keywords: *chemical, biological, radiological, nuclear, explosive, CBRNE, detection, reporting, expeditionary, navy special warfare, explosive ordnance disposal, unmanned aerial vehicles, model-based systems engineering, man-machine teaming*

Background
A highly mobile and flexible capability for detecting CBRNE characteristics within a confined or open area in a time-constrained environment does not exist. Small NSW and EOD units, in support of distributed maritime operations and expeditionary advanced base operations, are needed to rapidly report CBRNE status to a carrier strike group, surface action group, task forces, or to emergency operations centers. Because of the nature of CBRNE hazards, an aerial vehicle approach is required to prevent the spread of contamination, ensure the safety of small tactical units, and maintain stealth in a non-permissive combat environment.

Combining an aerial vehicle, a CBRNE sensor, and a link 16 communication system creates a SoS that provides more capability than the stand-alone systems. The SoS must be created to confirm or deny

CBRNE presence organically and to reach back to Joint Force ashore and afloat assets, national labs and intelligence centers, and other entities for follow-on support for retrieval, containment, direct assault, or joint fires. This SoS must be rugged, survivable to external threats, man-portable, requiring low-maintenance, and cost-efficient if vehicles or equipment must be disposed of or abandoned. The CANARY SoS is intended to support DoD find, fix, finish, exploit, analyze, and disseminate tasks that are essential for conducting operations to counter threats overseas and close to home.

The CANARY SoS was designed through the application of systems engineering and architecting to transform operational needs into a description of system performance parameters and a system configuration. Working closely with the sponsor, this was accomplished using an iterative, MBSE process of definition, synthesis, analysis, and design with the intent to provide the baseline necessary to transition into real-world operational testing and evaluation. This baseline design, in accordance with DoD standards and systems engineering life-cycle orientation, was used to determine suitability of potential system candidates and to screen three UAVs: the SkyDio, SkyRaider, and the NOVA 2. Prior to system selection, a simulation was performed to evaluate which performance characteristics have the greatest impact on the MOEs. Primary MOEs for the system include the time in which the system can detect, analyze, and confirm the presence of a threat, and the percentage of threats successfully confirmed. A script using the MATLAB programming platform was created to run and analyze various system configurations through an operationally representative scenario. The configurations tested had performance characteristics representative of the previously listed candidates and other available representative UAVs.

Findings and Conclusions

Based on results of simulation analysis, the number of deployed UAVs has the greatest effect in reducing the chance of failure, with UAV battery life following close behind. The interaction between the number of UAVs and battery life, and the interaction between the number of UAVs and UAV speed also have significant effects. A potential failure mode for the system is the UAVs limited battery life. With this in mind, employing more UAVs would allow the system to complete its search of the exclusion area faster while compensating for UAVs whose batteries die. Alternatively, with a larger battery pack on each UAV, the system can last for a longer period, reducing the probability that the UAVs run out of battery before finding the threat.

In addition to the simulation, further analysis considered the ability of the three candidates to meet overall system requirements. While operational performance involving the UAVs was at the forefront for the simulation analysis, this additional analysis ensured that the integration with CBRNE sensors, data modules, and communication networks were also addressed in this study. A clear advantage for the SkyRaider is that it is a proven POR, whereas the SkyDio and NOVA 2 require developing and evaluating performance metrics in vital areas such as the ability to detect CBRNE sources once integrated with sensors. The endurance, speed, and lift capacity of the SkyRaider are also superior. This placed the SkyRaider clearly ahead of the competition despite having almost three times the weight and double the size of the UAV body compared to the other two candidates. While battery life and speed prove to be significant positive traits for the SkyRaider, the SkyDio and NOVA 2 are more appealing in some respects because they are less cumbersome. The shorter battery life of the NOVA 2 hinders its ability to perform outlined requirements, which are viewed as outright failures without testing. Similar controller limitations from the high-level requirements analysis are also apparent for the SkyDio.

The SkyRaider dominates in most of the requirements analysis due to physically superior aspects but more importantly due to its proven operational history. It is additionally important to highlight that for every CBRNE sensor available, the SkyRaider is capable of housing and lifting them to the target and performing a full mission profile. However, the ability of the NOVA 2 to navigate and prosecute confined spaces is an important trait, and the SkyRaider and SkyDio would need considerable hardware and software updates to the NOVA 2. Based on this research, we recommend the SkyRaider as the current long duration CBRNE operations option when provided with adequate support and long-term sustainment.

Recommendations for Further Research

Further research should focus on three areas. First, the selected unmanned aerial vehicle (UAV) system of systems (SoS) must demonstrate integration with supporting systems. The ability for these UAV ensembles to integrate with a data module and Link 16-capable systems may be possible but was not confirmed. The ability to take data onboard chemical biological radiological nuclear and explosive sensors and push that information out is an essential task for the chem/bio agent nuclear and radiological yield (CANARY) SoS. Second, the means to charge power sources in an expeditionary environment needs to be developed or integrated if it exists. If personnel are in a field setting long enough, all batteries could expire, making the CANARY SoS added dead weight. Finally, there is a clear need for a full CANARY SoS operational test and evaluation. The analysis from this study covered components of the CANARY SoS. Their integration and use as a complete SoS could return more favorable or degraded results. The entire architecture for the CANARY SoS needs to be exercised and should include all available data for the systems to include propriety and classified.

References

None

NPS-22-N357-A: Hydrogen Fuel in Support of Unmanned Operations in an EABO Environment

Researcher(s): Anthony Pollman, and Paul Beery

Student Participation: Rachel Meyen-Faria, Bradley Petersen, Vanny Prak, and Jonathan Schweichler

Project Summary
This project conducted an operational analysis of the utility of hydrogen fuel to support unmanned systems in an Expeditionary Advanced Base Operations (EABO) context. The project developed a systems architecture to identify the relevant subsystems and design considerations for the construction of a hydrogen generation system. A discrete-event simulation model was created, using the ExtendSim software, to examine alternative system configurations and assess the sensitivity of candidate designs to alternative unmanned system operational concepts. Particular focus was given to the electrolysis power source; the study considered solar generation, low performance (rated for one kW) wind generation, high performance (rated for three kW) wind generation, and tidal/wave generation. Additionally, the project systematically varied both unmanned system and environmental characteristics as part of a designed experiment. Results indicate that the power generation type has a larger impact on operational performance than any environment factors, as well as the design or employment of the associated unmanned systems. Specifically, solar generation is the preferred alternative for hydrogen generation.

Keywords: *hydrogen fuel, hydrogen generation, alternative fuel, discrete-event simulation, expeditionary advance base operations, Littoral Operations in a Contested Environment, LOCE, Expeditionary Advanced Base Operations, EABO*

Background
Navy and Marine Corps planners developed the Expeditionary Advanced Base Operations (EABO) concept of operations to provide maritime commanders with more options for future sea control operations. EABO is envisioned as complementary to Littoral Operations in a Contested Environment (LOCE), which provide specificity regarding the concept for logistical support to multiple EABO sites. These concepts align with recent guidance, notably NAVPLAN 2021 and the Tri-Service Maritime Strategy, which detail the importance of unmanned systems capabilities to future warfighting. Many unmanned undersea and aerial systems currently in development are looking to alternative energy sources, including hydrogen, to maximize operational reach and persistence. These concepts and directions define a future combat environment that demands risk-worthy platforms to perform sea denial as a low-signature "inside force” that is untethered from a large petroleum supply chain. This study was motivated by that guidance and assessed hydrogen requirements for use as a fuel in an EABO environment to inform development of a capability evolution plan.

Use of hydrogen as a fuel in both EABO and LOCE requires consideration of several importation design considerations. The EABO and LOCE concepts both rely on mobile, low-signature forces. An idea that is repeated in both concepts is the distribution of unmanned systems across multiple sites. While there are numerous operational advantages to this distribution, it creates challenges for logistics and support. Specifically, each concept has the potential to create substantial stress on the fuel distribution network for both the Navy and Marine Corps. Employment of alternative fuels that can be generated in theater represents a potential solution to decreasing the stress on fuel distribution networks that may come from increased use of unmanned systems. Because hydrogen fuel can be generated through harvesting of seawater, it is a particularly attractive alternative fuel type. However, realization of hydrogen as a fuel for unmanned systems presents challenges that do not exist with conventional fuels. A major challenge is generation of electricity to power the hydrogen fuel generation. This report preliminarily considered the following electricity generation techniques: coal, natural gas, solar, geothermal, hydroelectric, biomass, wave, wind, and nuclear and directly implements solar, wind, and wave electricity generation techniques into the analysis of alternatives. Additionally, hydrogen fuel use requires a defined strategy for hydrogen generation. This report considered the viability of hydrocarbons, biohydrogen, photocatalytic solar, and electrolysis solar as alternatives, with electrolysis being the option considered as part of the analysis of alternatives. Finally, hydrogen storage was considered, with gas, liquid, and metal hydrides examined as potential alternatives. Given the expected timeline for this study, gas was the only option considered as part of the analysis of alternatives.

Using that expected timeline as a starting point, this work examines scenarios for hydrogen use as a fuel in an EABO environment. These scenarios model a hydrogen fuel distribution system with an emphasis on hydrogen generation and storage, the electrolysis mechanism employed to support hydrogen generation, the number of employed hydrogen generation systems, and the operational employment of unmanned vehicles that utilize hydrogen fuel.

Findings and Conclusions

To assess the viability of hydrogen fuel, this project utilized a discrete-event simulation in a software program called ExtendSim. The ExtendSim model simulates multiple EABO operational sites distributed across an island chain. Each site utilizes a combination of Unmanned Surface Vehicles (USVs), Unmanned Undersea Vehicles (UUVs), and Unmanned Aerial Vehicles (UAVs). Because the focus of this project was not the detailed representation of the unmanned vehicles, the performance and operational characteristics of the unmanned systems at each site were randomized and each vehicle was treated as a generic Unmanned Vehicle (UxV). At each site, the model simulated generation of hydrogen fuel and refueling of UxVs. The model assumed that, since the EABO and LOCE concepts emphasize distributed operations, each hydrogen generation system can operate without demand for external resources. This means that each hydrogen generation system had the capability to generate electricity and subsequently power the electrolysis of seawater into fuel. Additionally, there was an assumed constraint on the size of the hydrogen generation system. The model assumed that the system was transported to the site by a CH-53 helicopter, which dictated limitations on both size and weight.

Generation of hydrogen fuel using seawater was modeled as a series of five events: generation of electricity, processing of seawater, performing electrolysis, storing of hydrogen, and transfer of hydrogen to each UxV. Electricity generation was modeled in particular detail to represent three alternative generation techniques: solar, wind, and wave. Solar electricity generation was modeled using a sine wave and an assumption of a ratio of 12 hours of sunlight to 12 hours of zero sunlight (corresponding to a 50% duty cycle). Wind electricity generation was modeled using two alternative physical systems, one with a rating of one kW and a second with a rating of three kW. The electricity generated by each wind system was modeled by surveying candidate wind turbine systems, observing daily averages for power generation, dividing by time to get an average power by minute, and multiplying by a uniform distribution to introduce randomness. Finally, wave systems were modeled similar to the wind systems, with the note that power was generated as pulses, rather than constants. Once electricity was generated, the model simulated electrolysis when there was sufficient electricity to perform electrolysis for one minute (the time step used in the model). The model assumed that each hydrogen generation system was equipped with nine-kilogram tanks for storage of hydrogen fuel with a compression of 1.35 kilowatts per kilogram. The stored hydrogen fuel was used to refuel UxVs, which were deployed for operational use and arrived at the system at random intervals. 61,440 runs of the simulation were conducted across the following set of input variables: number of UxVs, UxV tank size, UxV hydrogen burn rate, UxV operational duration, UxV travel time to operational locations, electricity generation type, and number of electricity generation systems. Analysis suggests that solar electricity generation has the largest impact on mission success.

Recommendations for Further Research

This work used a discrete-event simulation model tailored to assess alternative strategies for the use of hydrogen fuel in an Expeditionary Advanced Base Operations (EABO) environment. The model assessed the viability of alternative electricity generation strategies to support hydrogen generation that is decoupled from traditional fuel chains via harvesting of hydrogen from seawater. The model was exercised for a sevenday timeframe (10,080 minutes) and systematically varied the following as part of a designed experiment: quantity of Unmanned Vehicles (UxV), UxV tank size, UxV hydrogen burn rate, UxV travel time to mission area, UxV operational deployment duration, hydrogen refuel rate, electricity generation type, and number of electricity generation systems. The analysis shows the use of solar electricity generation, rather than wind or wave approaches, has the largest impact on operational performance. Notably, approximately 10 solar devices are able to keep 30 UxVs refueled over a one-week timeframe. In comparison, the next-highest performing alternative, a 3 kW-rated wind turbine, requires approximately 20 systems to refuel 20 UxVs. The other electricity generation types considered (a 1kW rated wind turbine and a wave generator) are only able to support an average of 14 UxVs.

Beyond the type of electricity generation system, there were limited operational insights that warrant further investigation. Statistical analysis indicated that the hydrogen burn rate for individual UxVs was statistically significant; however, the operational impact appears to be minimal. Hydrogen burn rate was modeled from 2.5 grams per minute to 3.5 grams per minute, and the reduction from the maximum to the minimum value only allowed support of a single additional UxV. The interaction between input variables was also assessed with similar results. The only interaction that resulted in potentially actionable operational recommendations was the interaction between the number of UxVs and the operational employment duration of each UxV. The results indicate that in extreme scenarios, specifically a single UxV operating with a very short mission duration, the hydrogen generation system may not be able to generate hydrogen quickly enough to support refueling at the rate which the UxV will require. This suggests that, in scenarios where missions are expected to be extremely short, it may be beneficial to have additional UxVs on hand to serve as spares, rather than waiting for refueling.

Direct follow-on research can be dedicated to a comparison of the preferred solution from this project to other alternatives that were beyond the scope of this research. Solar appears to be a more promising technology in the near term than either wind or wave for hydrogen generation and may warrant additional emphasis. The results suggest investigation that compares hydrogen fuel to other potential fuel types, especially nuclear, may be worthwhile using a similar approach. Particular interest exists in the development of an operational effectiveness model to compare alternative strategies for the harvesting or generation of alternative fuels in theater, with emphasis on comparison of alternative (e.g., hydrogen, nuclear) fueled unmanned systems to conventionally fueled unmanned systems.

References

None

U.S. Fleet Forces Command (USFF)

NPS-22-N090-B: Assessment of Nighttime Airborne Visual ASW Capability

Researcher(s): Oleg Yakimenko

Student Participation: LT Justin Goff USCG, and Alexander Elbrecht

Project Summary
Rapid developments in small unmanned aircraft systems (sUAS) are accelerating their extensive deployment in the commercial and military communities. Combining low-light imaging sensors and advanced signal processing mounted on a sUAS can provide a fiscally responsible capability for nighttime subsurface object detection for the naval and merchant vessels and contribute to anti-submarine warfare (ASW). Low-light sensors mounted on sUAS systems can leverage marine bioluminescence as a naturally occurring object enhancement to detect, track, and potentially identify subsurface objects in the vicinity of vessel traffic. This report presents the results of initial attempts to collect and process imagery of relatively large moving objects in the shallow waters in Monterey Bay, California.

The preliminary tests with low-flying sUAS with affixed Sony UMC-R10C and 10-band MicaSense Blue/RedEdge-MX dual payload (20-megapixel and 1.2-megapixel per band sensors, respectively) showed concerns with the percentages of pixels per image based on the altitude of the aircraft, dictating a need to reduce experimental altitude based on the sensor specifications to improve the identification of a subsurface object at shallow depth. Imagery obtained using an affixed SBIG STC-428 photometric complementary metal-oxide semiconductor (CMOS) -based 7-megapixel sensor showed challenges with the exposure time creating elongated imagery and the need to use a filter to focus the sensor on the specific wavelength of light for bioluminescence detection. The lessons learned were reported to the sponsor. It is suggested to conduct some additional lab tests and low-altitude flights using a 40-megapixel sensor with a multirotor UAS launched from the ship.

Keywords: *anti-submarine warfare, bioluminescence, low-light and multispectral sensors, image processing, unmanned aircraft systems*

Background
In lieu of a submarine, this research attempted to detect a large marine mammal. If successful, the same methodology would then be applied to anti-submarine warfare. Subsurface collision by naval and merchant vessels is a growing safety, security, and environmental concern. In 2007, the International

Whaling Commission (IWC) launched a long-term initiative to collect and analyze information about reported ship strikes, both historic and current, aiming at identifying “hot spots” where large numbers of whales coincide with busy shipping lanes. Satellite tracker data that were placed on 14 whales off the coast of northern Chilean Patagonia and publicly available shipping information indicates that whales feed in spaces subject to intense marine traffic. To date, IWC has identified 12 hot spots and has logged at least 1,200 collisions between ships and whales globally (Bedriñana-Romano et al., 2021).

Currently, technology such as radar is insufficient for subsurface object detection, and there is no other system in place for nighttime subsurface detection in real time. The use of sUAS leveraging bioluminescence for this application has been proposed after operational photography of a school of tuna was captured off the coast of California (Brodie & Donaldson, 2021). The use of aerial imagery for detecting subsurface marine mammals is not new and has been tested successfully many times in daylight operations (Schoonmaker et al., 2011). This research sought to determine the field feasibility of combining this naturally occurring image enhancement phenomena with advanced image processing to further the research in nighttime subsurface object avoidance.

To detect bioluminescence at night this research relied on using a range of small sensors that can be carried aboard a typical commercially available sUAS or tactical UAS of a RQ-21 class. Indeed, in the case of sUAS, the major constraint is the size of the sensor. The search for all feasible commercially-available sensors resulted in choosing the 10-band MicaSense Blue/RedEdge-MX dual camera system and combined Sony UMC-R10C and 5-band MicaSense RedEdge-MX. This research also involved building another sensor inhouse. To this end, a CMOS camera with a high light sensitivity and a fast readout was chosen and combined with a Nikon lens and a bandpass filter for blue light.

Data for the experiments was captured from the sensors onto secure digital (SD) memory cards. After completion of any experimental run, the SD cards were removed and the data was transferred to a computer for processing. A combination of Agisoft and MATLAB software suites were used to post-process the imagery. Agisoft photogrammetric processing allows for creation of orthomosaic overlays of sensor data by stitching together images from preprogrammed mapping patterns into a single orthographic image. MATLAB Image Processing Toolbox allowed for detailed analysis of the imagery—specifically, enhancement to bring out underlying or fine detail.

Findings and Conclusions

When flown at 120m mean sea level (MSL), the MicaSense RedEdge-MX sensor’s image resolution of a gray whale of a typical length of about 14m and width of 3.5m occupies 7,666 pixels or 1% of the image. The assumption is that in the case of bioluminescence presence, the amount of light collected by 1% of the area of the sensor should suffice to detect or even identify a whale. The strength of bioluminescence emission would then define sensor exposure. At night, it may require extended time to capture enough emitted light, but this creates a problem. With a sUAS flying at low altitude at cruise speed of 17m/s, compatible with the speed of the ship, longer exposure (which would be required to capture weak bioluminescence emission) means image shift. For longer exposure times this shift can be relatively large, especially for the lower altitudes.

Like in the case of a commercial-off-the-shelf MicaSense RedEdge-MX sensor, when using an inhouse-built CMOS sensor, a 14m×3.5m whale would occupy 19.3% of the image if flown at 400m MSL and 5.5% when flown at 1,400m MSL. While this performance of the black-and-white low-light sensor is still acceptable, the image shift for a faster flying platform may become an issue. Obviously, with a much longer exposure, a whale would appear not as it would be seen during the daytime. The effect of the stretched image, caused from the movement combined with the exposure time, could be calculated and processed to produce a clear image. It would also be possible to combine a stack of images with lower exposure times. If the observed object changes its pose or shape, as may be the case if a whale moves, the result will not be a sharp image.

To ease the process of finding a subsurface object in the ocean at night (using the light from bioluminescence) it is necessary to avoid other light-emitting sources and reflections. Therefore, it is natural to use a narrow blue bandpass filter with a fitting bandwidth of 460 nm to 490 nm. Another practice is to focus on times when the moonlight is low, either at new moon times or after moon set when the moon has fallen below the horizon.

The conclusion is that developing a novel nighttime subsurface object detection capability is a very challenging task. The test results showed that even with applying a narrow blue bandpass filter and using long exposure time settings, getting a clear image of a moving subsurface object was almost impossible. Since the entire technology relies on unpredictable bioluminescence emission, which is typically very weak anyway, the current state-of-the-art miniaturized sensors that a typical sUAS can carry does not seem to facilitate a reliable detection capability to contribute to ASW.

Recommendations for Further Research

At this point in the research there are no field-ready findings from this report. However, three topic areas are ripe for further research with a potential for field implementation. First, sensor specification and settings must be researched further for use at night. Specifically, further research should investigate the effect of analog and digital gain optimized with sensor aperture and exposure time to reduce image shift and create a clear image of a moving target while the aircraft is moving.

Secondly, once those sensor specifications are researched, more test trials could be conducted throughout the year to capture experimental data with different levels of bioluminescence. The use of both multirotor and fixed-wing small unmanned aircraft systems must be explored in conjunction with offshore stationary platforms to detect and track the bioluminescence.

Lastly, algorithms to scan and isolate images that may contain low levels of emitted bioluminescent light could be developed. This will further the research by helping to comb through the thousands of captured images during each flight, but it will also be a step toward real-time imagery processing once the sensor systems are matured.

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NPS-22-N181-A: COTS AI/ML Technology for Data Fusion and Track Management

Researcher(s): Victor Garza, Brian Wood, Shelley Gallup, and Douglas MacKinnon

Student Participation: CPT Wei Goh

Project Summary

The Navy, and specifically Naval Information Forces, lacks the ability to fully employ artificial intelligence/machine learning (AI/ML) effectively to assist with data fusion and provide quick and timely analysis of the common operating picture/common tactical picture (COP/CTP). Other industries use this rising technology to enhance their analysis fusion. To help bring the Navy up to date, we examined multiple data streams such as geospatial intelligence (GEOINT) and radar data sets to fuse this information quickly and with greater accuracy of managing positive identification of tracks to provide the most current intelligence directly to the commanders for their decisions.

We performed an analysis of the ability to use AI/ML by using commercial off-the-shelf (COTS) software to automate filtering and demonstrate accuracy of multiple data streams into the Navy's COP/CTP for specific use by Naval Information Forces. Multiple data sets were integrated and filtered with automation

to provide quick and timely analysis, while increasing speed and accuracy of managing positive identification of tracks, and developing the COP.

During our research, we created an ML pipeline that processes data from a simulation to train and test ML models that can be used in a Kalman filter (KF) system. We improved the KF by adding a learning component, called the ML-KF, which used sensor measurement errors to make more accurate predictions. The simulation system provided accurate data to train the learning component of our KF model, which means simulation can be a useful method for developing and testing ML models. These trained models may be able to be used in real-world situations in the future.

Keywords: *artificial intelligence, AI, machine learning, ML, intelligence fusion, data analysis, human-machine interaction, decision aids*

Background

The Navy, particularly the Naval Information Forces, is struggling to effectively utilize AI and ML to process and analyze data to assist with data fusion and provide analysis of the COP/CTP. Other industries have adopted these technologies to improve data fusion and analysis. To improve, the Navy has studied using various data sources, such as sensor track data, GEOINT, and radar data, to more efficiently and with greater accuracy, merge information and provide for the management of positive identification of tracks and furnish the most current intelligence to commanders for decision-making.

We set out to investigate whether ML models can improve the accuracy of state estimation (predict the position, velocity, and acceleration of an object based on its previous motion, and other factors) in a COP/CTP. We used a mathematical approach to study how adding a machine learning component to the KF algorithm can improve its performance.

Our research focused on the analysis of multiple sensor data streams for ingestion into AI/ML systems. Research also identified and analyzed relevant previous work on use of existing machine learning algorithms or techniques that could be usefully applied to the analysis of sensor data, searching for, and focusing on, those relevant and applicable to the COP/CTP and filtered for expedient track identification.

We consulted subject matter experts on background material and obtained feedback on appropriateness of proposed approaches and methodologies. We also identified principles and tactics for integrating machine learning into operational scenarios. A thesis student analyzed proposed opportunities for ML and data flow applications and determined their value added in the context of surface warfare.

We have studied the Minotaur common operating picture and determined its suitability for the task. Examples of several COTS applications have been effective in providing promising results. We reviewed previously proposed solutions, identified potential future applications, and evaluated their utility for the Navy.

Findings and Conclusions

Our results showed that adding a machine learning component to the KF algorithm can increase the accuracy of state estimates by about 20%. In summary, our findings suggest that:

- We have developed a workable ML operations pipeline that ingests data from a simulation to train, validate, and test ML modules for subsequent deployment in a KF system. The methodology, dataset, and models generated are reproducible and replicable, as the code base and frameworks used for this development are open source.

- We added a learning component to a common algorithm called the Kalman filter. This improved the KF's ability to estimate the state of a system. Our modified version of the KF, called the ML-KF, was able to use a matrix of sensor measurement errors to improve the KF's predictions. As a result, the ML-KF provided more accurate estimates than the regular KF.

- We were able to train the learning component of our KF model because our simulation system provided accurate data that we could use to evaluate the model's performance. This shows that simulation can be a useful tool for developing and testing ML models. In the future, we may be able to use these trained models in real-world situations.

Based on the findings of this research, it is recommended that future study continue to explore this topic and build upon the knowledge gained here.

Recommendations for Further Research

We have conducted research on and evaluated the applicability of the Minotaur common operating picture for suitability for the task at hand.

During the execution of this research, we explored multiple interoperability architectures to determine the feasibility of passing our simulation data to a command-and-control (C2) system while the artificial intelligence/machine learning (AI/ML) track identification algorithm was operating. The simulation we used was Command Professional Edition, which has the capability of passing simulation data packets as defined by the Institute of Electrical and Electronics Engineers Standard for Distributed Interactive Simulation -- Communication Services and Profiles 1278.2-2015.1 Within this standard, we were seeking to utilize the data contained in the entity state protocol data unit (ESPDU) and map that to a tactical messaging format which can be processed for display on the C2 system. The System of Systems Technology Integration Tool Chain for Heterogeneous Electronic Systems (STITCHES) was the interoperability architecture we used for experimentation. It is currently under development and is managed under the Secretary of the Air Force – Acquisition, Technology and Logistics (SAF/AQ).

The Air Force developed STITCHES to support homogeneous, fixed-configuration weapons systems. When creating weapons systems for the Department of Defense (DoD), we need to consider that some of those systems will be operational for 30+ years. STITCHES has been designed to ensure system interoperability with emerging systems as the force modernizes.

Akin to STITCHES, we have also created a similar contact report in the Over the Horizon - Gold (OTH-Gold) messaging format. Since the ESPDU and contact report contain similar data, our next research step is to map the latitude and longitude of each AI/ML algorithm-identified track into an OTH-Gold message for display on the Intelligence Carry-on Program (ICOP).

Both the STITCHES and OTH-Gold messaging format integration will provide valuable enhancements to the ICOP COP/CTP platform for potential implementation by the sponsor.

Future work may include further development of these methods and technologies.

References

None

NPS-22-N206-A: Commercial Communications Data Fusion Analysis

Researcher(s): Arijit Das, Neil Rowe, Walter Kendall, Bruce Allen, and Peter Ateshian

Student Participation: Aroshi Ghosh, Lahari Yallapragada, and Stefan Didoszak

Project Summary

Commercial navigation systems are now being used by military vessels, data that is available for all to use, which opens up the possibility of detection by non-military entities. The Automatic Identification System (AIS) is one such sea-vessel transmission that is used in commercial navigation, received by satellites and stored on servers for all to access. The fiscal year 2022 (FY22) study was based on a prior thesis (Sollish, 2017) that used AIS data to track ship movements, coupled with vessel identification to localize the ships. Datasets of AIS were downloaded from open-source data portals, and cleaned and prepped (data wrangling) for Artificial Intelligence (AI)/Machine Learning (ML) algorithms. Since ML is a data dependent science, the data was analyzed using various algorithms simultaneously by Weka, an open-source AI/ML software tool, and the models built were evaluated. The model was then used to classify the ship types and a confusion matrix was created. All tasks were automated and done using the Python programming language and associated software libraries. For visual feel and understanding of outliers and gaps, the ship tracks were plotted using graph library packages. Data wrangling on AIS datasets was programmed in Python and the code executed. The raw AIS data was well morphed for suitability to

AI/ML algorithm processing; data non-ambiguity was removed before AI/ML model building. For future work, other electromagnetic (EM) sources (radar, satcom) and satellite imagery data will be fused with AIS to get better triangulation of naval vessels. The FY22 effort used files as opposed to a relational database (DB) schema, and handling data growth with Big Data technologies like Hadoop Distributed File System (HDFS), all needs to be explored.

Keywords: *deception, data fusion, confusion matrix, automatic identification system, AIS, satcom, radio, database, data wrangling, Structured Query Language, SQL, hadoop, analytics, artificial intelligence, machine learning*

Background

As commercial communication and navigation systems proliferate, and their capability increases, some of these systems are also being employed by military vessels. For example, military systems might avail only commercial systems to conduct a mission, but not the full set of commercial systems used by "typical" commercial vessels. This study will look into analysis and correlation of electromagnetic signature of commercial communication, and navigation systems used by commercial and military vessels at sea.

The various EM transmissions can be AIS, satellite communications, or radar. The FY22 study focused on AIS (transmission of data from sea vessels and received by satellites to track movement), building upon a prior Naval Postgraduate School (NPS) thesis (Sollish, 2017). This study takes the learning from the thesis and applies it to tracking/classification of ship activity. AIS data collected can be downloaded from open-source portals for free. Such data has to be cleaned of irregularities, and prepped for processing by AI/ML algorithms. The grid of data thus served as the training/test dataset, which was then ingested into Weka, and a slew of algorithms were evaluated and a model was built. The model was used to predict the ship type and the results displayed in a confusion matrix, which shows the model efficacy. The algorithm/model which produced the highest efficacy was chosen. AI/ML algorithms/models and efficacy are very data dependent and can change with growth of data, thus an AI/ML software like Weka enables one to find the best fit algorithm as a part of its toolkit, that is, simultaneous evaluation of multiple AI/ML algorithms on the same dataset.

Preliminary study of the data was done to decide on the final grid of columns, so raw data was morphed as needed to make it well suited for an AI/ML algorithm in order to build a good model. All of the tasks were performed in an automated manner using Python programming language and libraries for data-wrangling and plots. NPS researchers consisting of AI/DB/Big-Data faculty and summer interns worked the project to complete the data wrangling in Python and build AI/ML algorithms/model to do the classification. Cleaned AIS data was also used to plot ship tracks, which gave a good visual on outliers and gaps.

Findings and Conclusions

The initial finding was about the quality of data obtained from free open-source data portals. Three key columns from the AIS dataset were used to build a key to uniquely identify a vessel, but some of the data in those three columns was missing, so those vessels had to be removed from consideration. After the key was built, analysis was done with the remaining columns, and even those had missing values, and thus more rows had to eliminated. After plotting the ship tracks there were gaps and outliers that confused the algorithms. Thus, finally only 30% of the data was useable for final AI/ML model training/testing. A better approach would be to get data from paid data portals, but in spite of these hurdles this study was able to get results with the remaining data.

The next finding was that the raw AIS data cannot be used as is and be input to a AI/ML software tool like Weka. The data has to be transformed by computing new columns that will make for a good AI/ML model build. An example added column is line segments, which are needed to complete the vessel tracks and turned out to be a good indicator of type. Other new columns included how long a vessel was out, and average acceleration. AIS data contain multiple rows of data on each vessel, so aggregation was another good technique. The best approach for getting data ready for a AI/ML algorithm was initial human assessment and study of raw data for vessel classification, followed by computation.

Once the data was ready for an AI/ML algorithm, the challenge was to select the best AI/ML algorithm, so a software tool was needed that would evaluate multiple algorithms for the best results. The choice of Weka turned out to be an appropriate fit. Weka has a feature called Experimenter which takes the same data dataset and then evaluates multiple AI/ML algorithms. Weka Experimenter selected a Random Forest algorithm which gave the best model fit and results. A Random Forest model aggregates the results of multiple decision trees and is a good generalized approach. The hope is that as the data changes the model will able to still classify well.

For any AI/ML model data, volume is important, as more data will only go to make the model better for classification. Laptops and servers with files can only go to a certain extent, so to handle data growth databases, Hadoop Distributed File System (HDFS) should be considered. The study found that the first transition step would be a Relational Database, followed by HDFS. The team did some preliminary evaluation of the DoN licensed Oracle Database and the Big Data HDFS architecture, and found it be a cost effective transition.

Recommendations for Further Research

The study used data from free open-source portals; this limited the volume of data available. Paid sources of data cover wide geographic regions and is more complete, with fewer missing rows and columns. This will reduce the time spent on data wrangling and mean less programmer coding time.

The data was all stored in files, thus not able to handle large volume. A future consideration is to store the data in a relational database schema which handles large data manipulation well with the Structured Query Language (SQL). SQL is easier to work with than writing code, so a larger community engagement at the preprocessing of data stage. When the data volumes exceed the limits of a database, a Big-Data architecture needs to be considered. The study evaluated cost effective solutions for implementing a Big Data parallel processing architecture such as the Hadoop Distributed File System (HDFS), and the next step would be to use a system like HDFS and benchmark processing times.

The primary focus of this study was automatic identification systems (AIS), but for validation several sources of ship activity needs to be used. A future version of this study should look at satellite imagery and other electromagnetic transmissions and correlate to AIS. This will involve contacting various vendors for each of the data sources and finding a common key to link all the data for triangulation.

For the topic sponsor to make this a production system, a team of computer scientists/engineers needs to be assembled who can work with the end user community to build a full product (software and hardware). A data center that can handle the data volumes and processing times needs to be made available. Dedicated multi-year funding is needed to make this effort a viable solution that meets the need of the community.

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NPS-22-N208-A: Bayesian Search Study for USW

Researcher(s): Roberto Szechtman, and Moshe Kress

Student Participation: LT Ryan Bailey USN

Project Summary

Adversarial submarine activity in the Atlantic has steadily intensified over the last few years. Furthermore, strategic adversaries have developed sophisticated and stealthy submarines, making them much more difficult to locate. This heightened activity, coupled with advanced platforms, has allowed the United States' adversaries to challenge its dominance in the underwater domain. Though extensive research has been performed on optimized search strategies using Bayesian search methods, most methodologies in the open literature focus on search for stationary objects rather than a search for a moving Red submarine conducted by a Blue submarine. Thusly motivated, we developed a model of an enemy submarine whose goal is to avoid detection. As the search effort is extended, a posterior probability distribution for the enemy submarine's location is calculated based off negative search results. We present a methodology for finding a search pattern that attempts to maximize the probability of detection in a Bayesian framework utilizing Markovian properties. Specifically, we study three different running window methods: a simple

network optimization model; a network optimization model that performs updates after every time-period for the entire time horizon; and a dynamic program that only looks two time periods ahead.

Keywords: *Anti-Submarine Warfare, Optimal Search, Bayesian Search, Markovian Movement*

Background

Submarine activity in the Atlantic Ocean has steadily intensified in recent years with the increased deployment of adversaries' submarines. Additionally, U.S. adversaries are developing highly capable and stealthy submarines equivalent to those in the U.S. Navy. Because of these developments, U.S. senior leaders have assessed that the Atlantic Ocean is no longer an uncontested battlefield; new considerable undersea threats have emerged. For example, in 2018, the USN reestablished the U.S. Second Fleet to counter adversarial submarine activity in the Atlantic (LaGrone, 2018). In addition, the Navy recently announced the creation of a new task force of destroyers specifically assigned to be ready on short notice to deploy for hunting submarines in the Atlantic (Shelbourne, 2021). Operationally, crews are receiving extra training and certifications prior to deployments, to ensure readiness to face the undersea threat from hostile submarines. The actions the USN is taking unambiguously illustrate the significance of the threat posed to national security by heightened hostile submarine presence in the Atlantic. Being able to quickly locate and track Red submarines, as they deploy to the Atlantic, is vital to national security. The Ohio-Class Ballistic Missile Submarines (SSBNs) were designed to be the survivable leg of the nuclear triad. Submarine crews on SSBNs, while on alert, are required to remain undetected so there remains a credible second nuclear strike capability, which offers the president additional flexibility in decision-making and presents a deterrence of nuclear and non-nuclear aggression by strategic adversaries. Hostile submarine activity operating in waters near SSBNs potentially degrades the survivability of the SSBNs, should the submarines detect and track them. The ability to quickly locate hostile submarines will allow commanders to adjust the location of SSBNs to maintain maximum assurance of their survivability and will help the Navy track the Red submarines to alleviate the threat of their weapons being deployed on the homeland.

From a historical perspective, Anti-Submarine Warfare (ASW) began in earnest during World War I to counter the Imperial German Navy's strategy of unrestricted submarine warfare (Cares, 2021). Since then, ASW has evolved into two categories: offensive ASW and defensive ASW (Cares, 2021). In offensive ASW, the goal is to hunt and kill enemy submarines (Cares, 2021). However, it is critical to note that during peacetime operations, the goal is modified to locate and maintain contact with the adversarial submarine (Cares, 2021). On the other hand, the goal in defensive ASW is to defend assets from being attacked by enemy submarines (Cares, 2021). What is common to both efforts is the need to efficiently find enemy submarines. Submarine commanders are given water-space within which to operate, information regarding a position of an adversary submarine, and possibly intelligence regarding the adversary submarine's mission. With this information, commanders are required to develop a plan to search for the adversary submarine, often over planning horizons (e.g., 12 hours). Our research is focused at facilitating this type of planning.

Findings and Conclusions

The ability to quickly locate adversarial submarines provides flexibility in the deployment of the USN strategic submarines, and it also provides security from attacks against the homeland. We developed algorithms that can aid decision makers aboard a submarine in their search for adversarial submarines. These algorithms may be further developed into operational decision tools that can be implemented during operations.

The first algorithm maximizes the probability of detecting Red over the time horizon, using a network optimization framework. The search plan is calculated once and without updates, assuming that Red is not detected in a searched cell. We then expand upon this algorithm by performing a Bayesian update of the position of a Red target after each cell search, assuming that the search is unsuccessful. Following a Bayesian update, a new search plan that maximizes the probability of detecting the Red target in the remaining search period is computed. The third algorithm is a dynamic programming model. The algorithm also makes use of Bayesian updates which assume the cell search is unsuccessful; however, in this algorithm, instead of maximizing the probability of detecting Red over the entire remaining planning horizon, we maximize the probability of finding Red in the next time period or, failing that, in the following time period.

To compare the three algorithms, we pose five scenarios where we vary the starting location of the Red target and the number of cells in which it may initially be located. The transition matrix governing Red's movement is the same in the first four scenarios; it permits Red to to move in a certain general direction. The fifth and sixth scenarios are more relaxed. For each scenario, 10,000 initial starting positions and routes are simulated.

Using the optimal search plans and the simulated routes for Red, we determine if Blue detects Red and during which period the search plan detects Red. We compute 95% confidence intervals for the probability of detecting Red and generate empirical CDFs to illustrate how the probability of detecting Red varies with time to compare the three algorithms. Additionally, for the first five scenarios, we calculate the computational time required to generate the search plan for each algorithm in CPU cycles.

The results of the first five scenarios are consistent: The second and third algorithms outperform the first algorithm, the third algorithm the second in four of the first five scenarios; however, in all five scenarios the 95% confidence intervals for the probability of detection overlap, meaning their performances are comparable. These computational results show that the third algorithm is the most computationally efficient, which makes it the best algorithm to implement in a search tool.

Recommendations for Further Research

We recommend in future research to explore non-perfect sensors where there are both false positive and false negative search results, and where the probability of detecting Red, if both submarines in the same cell, is less than one. This will allow for more realistic conditions where environmental factors play into how well an adversarial submarine may be detected. We also leave for future work relaxing the assumptions that the transition matrix is known by Blue and using concepts from Game Theory to explore worst-case transition matrices for Blue – the searcher. Finally, applying the work in this report to multiple search assets conducting the search concurrently is an important problem that may well require a different modeling approach.

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NPS-22-N215-A: Tactical ISR/C2 Integration with AI/ML Augmentation

Researcher(s): Randy Maule

Student Participation: Capt Jordan Figlioli USMC

Project Summary

NAVPLAN 2021 specifies distributed maritime operations (DMO) with a tactical grid to connect distributed nodes, and artificial intelligence/machine learning (AI/ML) at the tactical edge to support expeditionary advanced base operations (EABO) and littoral operations in a contested environment (LOCE) (Chief of Naval Operations, 2021). Joint All-Domain Command and Control (JADC2) is the vision for integrated command and control (C2). However, the architecture has yet to be fully designed and the intelligence, surveillance, and reconnaissance (ISR) and C2 hardware and software fully integrated. This project evaluates options for ISR and C2 integration at the tactical edge to support a universal common operational picture (COP), on tactical clouds, with AI/ML for decision support. We evaluate new innovations in tactical cloud hardware infrastructure, tactical cloud software operations on that infrastructure, and industry and government solutions for a universal COP able to operate at the far edge and synchronize with tactical commands and headquarters when communications are available, providing AI/ML for automation and decision support.

Keywords: *command and control, C2, intelligence surveillance and reconnaissance, ISR, common operational picture, COP, distributed maritime operations, DMO, littoral operations in a contested environment, LOC, expeditionary advanced base operations, EABO, Joint All-Domain Command and Control, JADC2, artificial intelligence, machine learning, AI/ML*

Background

My tests in the fleet, in the network operations centers, and in forward deployed shore commands throughout the 2000s and 2010s as part of the FORCENet sea trials for the Deputy Chief of Naval Operations (DCNO), Naval Network Warfare Command (NETWARCOM), and Joint Forces Command (JFCOM) provide the technical and operational foundation for this report. In our experiments we evaluated best-in-class tactical cloud infrastructure from industry and best-in-class C2 and ISR software from industry and government. The project herein integrates the DCNO, NETWARCOM, and JFCOM lessons learned and extends this research to address recent innovations that significantly reduce the space, weight, and power (SWaP) required for tactical edge infrastructure. This will enable us to further extend the tactical cloud to address the mobile devices of warfighters at the far edge. On this mobile cloud infrastructure, we evaluate sponsor requirements for an integrated C2/ISR universal COP, and CNO requirements for the DMO tactical grid, EABO, LOCE, and JADC2.

Findings and Conclusions

In this project we evaluated hardware and software options for tactical cloud edge nodes with integrated C2 and ISR services to support sponsor requirements for a universal COP. Our solutions additionally supported DMO, EABO, LOCE, and JADC2 objectives. We tested the new generation of low-cost, low SWaP hardware and emerging options for tactical cloud software to select the best-in-class solutions for far-edge tactical operations and mobile hybrid clouds. We evaluated recent software innovations that enable a transition from dedicated hardware servers and virtual machines to containers and micro-services that integrate C2 with ISR to provide a universal COP that synchronizes from headquarters, to forward deployed tactical commands, to far edge mobile devices. The tested configurations were assessed for both online and offline operations, to function in communication, spectrum and cyber challenged environments. We summarized options for a low-cost, low SWaP universal COP with AI/ML decision support for the topic sponsor.

Recommendations for Further Research

Future research may continue to refine the hardware and software configurations for lightweight tactical clouds suitable for extreme-edge deployments in challenged environments, integrating command and control (C2) with intelligence, surveillance, and reconnaissance (ISR) software and services into a universal common operational picture for warfighters that synchronizes with tactical commands and headquarters when communications are available—and when not, maintains persistent C2/ISR capabilities with a full suite of machine learning services for warfighters at the tactical edge.

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NPS-22-N250-A: Seabed Warfare and Target Folder Processes (Continuation)

Researcher(s): Shelley Gallup, Don Brutzman

Student Participation: No students participated in this research project.

Project Summary

Seabed warfare and open water strikes on targets of opportunity will include fighting in a joint theater-level environment. Prior to any open hostilities, it is imperative that the intelligence capabilities can establish areas or specific items of interest. In this unclassified but controlled unclassified information report, specific systems will not be named. There are three major participants in this study, the intelligence community, U.S. Navy undersea, and the Joint Task Force (JTF). These three participants are compared to find the best organizational "fit" to complete a joint task force input. Here, we assume that there are means for detection by platforms with acoustic intelligence (ACINT) capabilities; however, processes for assessing and assigning targets in a rapid fashion for inclusion into the Joint Fires Target Folders are immature at best, and difficult to describe and perform at worst. What is working, and what is not is described in general terms. Finally, an analysis employing Monterey Phoenix in a simple scenario and the observe, orient, decide and act (OODA) "loop" is provided, revealing that there are many paths through even a simple problem, with the potential of "emergence" of a system of systems arising. Monterey Phoenix was used to determine if a larger scale simulation could be conducted in future research.

This work's penultimate finding is that the ACINT paths do not support the needs of target folder planning or the use of this data to support time-critical decisions. The Joint Task Force Commander should determine from current and soon-to-be sensors what capabilities and limitations exist, with regard to making acoustic data available to the Joint Task Force Commander and adding to the Joint Targeting Folder processes.

Keywords: *acoustics intelligence; joint warfare; fires planning process; seabed warfare; autonomous sensors; OODA loop; observe, orient, decide, act loop*

Background

The general premise of this work is to adapt seabed and undersea warfare to the existing joint fires process and provide recommendations for any modifications required to allow joint fires processes to accommodate seabed warfare targeting procedures more-readily, especially determining the process and information. In this effort, "seabed warfare" means specifically targets of interest that are laying on the seabed floor, such as acoustic devices, communications listening devices near cables that enable fiber optic information to flow between nations, mines that are outside the littoral zones and anything in the water column that could be targetable under circumstances of critical time targeting. As such, the term "seabed warfare" is a general term.

Target acquisition, within time scales that allow them to be positively identified and meet criteria for kinetic or non-kinetic kill, will be part of the criteria for inclusion in Joint Targeting Folders. The first part of this effort was to review the Joint Planning Process documents to determine where the ACINT is mentioned as part of the target folder definition process. Here it is obvious that the term is not included, and that the processes are mostly general discussions of operations guidance. Second, a very crude determination of what current and near-term sensors are, was developed. This is important because it is obvious that getting data from these sensors and into the processes is difficult, and the physics related to acoustics in the ocean are very much involved.

Finally, revisiting the OODA loop was envisioned as a new way to relate to the problem. That is, sensors need to "observe" (find) from other acoustic energy in the ocean, that which is important. The "orient" segment means getting that data from the ocean and into a stream of data transmission. This is a current technical problem. Once, (and if) the data is transferred, it needs to be properly tagged with meta-data so that there is some contextual reference to that data. Finally, it needs to get to the right place, at the right time so decisions can be made. Other problems outside of the physics are the logistical support for these sensors (a separate NRP project) and the risks being taken as part of that support. Of interest at this last phase of the investigation is the use of Monterey Phoenix (MP). MP is used here to show that the negative feedback loops inside of the ACINT data stream can cause emergent behaviors that are not elicited by inspection alone.

Findings and Conclusions

As the maritime undersea competition continues to increase, relying to a very great extent on autonomy and manned platforms together, a new configuration of how ACINT is gathered, its command and control, and interconnectedness to the stream of other information has to be updated. A review of pertinent documents and instructions makes it clear that acoustic intelligence is an area in which there exists a large gap. Current Joint Publications do not include this intelligence directly, instead they rely more on "if it is important, it will get there." This is no longer adequate. Acoustic intelligence needs to be part of the planning process within the United States Navy in general and made available to the Joint Task Force Commander as theater target folders are being prepared.

A review of the OODA loop from different approaches shows that acoustic intelligence is not likely to be integrated in a timely way, except for prosecution of a target that is immediately within view. Instead, it is the entire panoply of new sensor capabilities that need to be tied together in an analytic and products "delivery system" to make the information useful for kinetic and non-kinetic warfare.

This research confirms what has already been known within the undersea community but is being further compounded by increased complexity of the systems architectures being proposed. It is highly related to another problem (logistics of undersea warfare) that is a separate and ongoing Naval Research Program project.

This research recommends the following actions:

1. Consider restructuring the organization around ACINT. Use of machine learning and focused artificial intelligence may be useful in getting the right data to the right place at the right time.
2. Create human-machine partnerships within the processing system so that context, intent, and timeliness can be better served.
3. Resolve authorities and priorities for data analysis and return to fleet users or to archives for later use.
4. Solve command and control and technical problems first. Meta tagging of data is essential. Logistics support of sensors is another topic but should not be intermingled here.
5. Use simulation and modeling tools to aid in sensing where it is needed most, with the right kind of acoustic sensors. Monterey Phoenix was used here and helps to show emergent behaviors.
6. Use war game sensor types, fields, logistics, data processing within a forward force scenario in the Indo-Pacific region.
7. Update the Joint Publications to reflect the role of ACINT and inclusion within Joint Targeting Folders.
8. The seabed is going to become increasingly important as an area of warfare. More funding and attention needs to be paid to think through problems and to implement recommendations above.

Recommendations for Further Research

This research does not explicitly solve the problem of Joint Task Force inclusion of acoustic intelligence in Target Folders, but rather describes the problem in a more rigorous way. Future research will have to consider the command and control of sensor assets and physics of the ocean in which to communicate data, and new strategies for employing these assets. Although the initial figures at the beginning of this report show where areas of opportunity exist, there are likely areas that we are not yet considering that are equally important. Finally, these capabilities are both offensive and defensive, and they are tied to policy decisions with our partners in the region. All of these are rich areas for further research.

References
None

NPS-22-N347-A: USV and UAV Teaming for ISR-T Capability

Researcher(s): Brian Wood, Shelley Gallup, Douglas MacKinnon, and Victor Garza

Student Participation: LT Scott Burbach USN, and LT Marc Samonte USN

Project Summary
This report investigates the application of current and near-term operational architectures to enable unmanned aerial vehicle (UAV) and unmanned surface vehicle (USV) teaming for intelligence, surveillance, reconnaissance, and target acquisition (ISR-T) missions for distributed maritime operations (DMO). The purpose of this research is to conduct an analysis, using the Joint Capabilities Integration and Development System (JCIDS) DOTMLPF-P (doctrine, organization, training, materiel, leadership & education, personnel, facilities, and policy) methodology, of UAV-USV teaming potential for integration into DMO. Deficiencies of current operational architecture design that inhibit or deny this capability are noted for correction for near-term operational architecture advancements. Doctrine, training, and leadership & education were determined to be the three DOTMLPF-P categories needing the most attention before UAV-USV teaming in the ISR-T environment can move forward. We recommend that the first priority is to have UAV-USV teaming doctrine be established before the US Navy moves forward with executing UAV-USV teaming in the fleet. Second, we recommend initiating integration of teamed UAVs and USVs into carrier or expeditionary strike groups to supplement or replace current assets for ISR-T missions and enable the transition of the fleet to support DMO.

Keywords: *unmanned surface vehicle, USV, unmanned aerial vehicle, UAV, intelligence, surveillance, reconnaissance, targeting, ISR-T, teaming, distributed maritime operations, DMO*

Background
DMO requires ISR-T information on enemy warships. The ranges of current anti-surface missiles far exceed organic sensing capabilities. Space-based assets may not be operative, or otherwise tasked pre-empting their use in locating threats. One solution is to use USV launched UAVs to provide the ISR-T capability.

We first established baseline information for UAVs, USVs, DMO, operational architectures, and UAV-USV teaming related experimentation. The classification systems used for both UAVs and USVs were discussed as was a deeper dive into commercial and defense related concepts. The implementation challenges of UAV-USV ISR-T into DMO were scrutinized. Seven separate architectures were reviewed to determine their viability in the UAV-USV teaming arena. We also looked at implementation challenges/vulnerabilities and two UAV-USV ISR-T experimentation events.

The Navy's JCIDS DOTMLPF-P methodology was used to analyze the status of UAV-USV teaming and what shortfalls must be addressed before proceeding with its execution.

We consulted subject matter experts on background material and obtained feedback on appropriateness of proposed approaches and methodologies.

Eight DOTMLPF-P categories were examined for changes needed to allow UAV-USV teaming to be operated at its fullest potential. The amount of work needed, and priority placed on that work determined the effort required to execute this capability recommendation.

D-Doctrine	How the military fights its conflicts.
O-Organization	How the military is organized to fight.
T-Training	How forces are prepared to fight from basic training through unit/joint exercises.
M-Materiel	Equipment/systems needed to fight and operate effectively.
L-Leadership & Education(L)	How leaders (at all levels) are prepared to lead the fight.
P-Personnel	Does current manning allow for this capability to be used to its fullest potential?
F-Facilities	Are military properties and installations being used to fill in a capability gap?
P-Policy	Department of Defense/other policy issues that could prevent implementation of changes in DOTMLPF-P categories.

Current UAV-USV teaming for each category was given a grade (1-5) indicating what needs to be done to reach its highest level of realization: 1-poor current implementation/significant changes needed, to 5-fully realized/minimal changes needed (Schuck, 2022).

Grade 5	Fully realized; minimal work needed to reinforce current plans/documentation.
Grade 4	Mostly implemented; limited additions needed for full realization.
Grade 3	Partially implemented; major additions needed for full realization.
Grade 2	Information/procedures exist, but not very extensive, or out of date.
Grade 1	Little to no documentation/discussion; large amounts of work needed.

Each DOTMLPF-P category has a priority value indicating the importance of the criterion towards the success of UAV-USV teaming. Priority values are independent of grades. Even though a category may have a high grade (e.g., 5), it may be a low priority for the success of the system (Schuck 2022).

High	Essential for fully executed teaming to be at its highest form of completeness
Moderate-High	Required for fully executed teaming; can be under development, but progress towards completeness needed soon
Moderate	Necessary for fully executed teaming; can be under development
Low-Moderate	Not necessary, but complete development would help towards execution of teaming
Low	Not necessary for execution of teaming.

Findings and Conclusions

DOTMLPF-P analysis was conducted to determine the feasibility of, and changes required within each category for the successful implementation of UAV-USV teaming in the ISR-T environment.

The below data provide decision analysis showing compilations of the different categories and their status relative to one another. Only doctrine is completely lacking in support or development (grade of 1), and most (five with scores of 4 or 5) have some progress to be made for the UAV-USV teaming capability to be successfully implemented meaning that little to no additional work or effort needs to be accomplished within that category to support full implementation of UAV-USV teaming.

Category	**Grade**	**Priority**
Doctrine	1	High
Organization	5	Moderate-High
Training	3	High
Materiel	5	High
Leadership & Education	3	Moderate-High
Personnel	5	High
Facilities	4	Mod
Policy	5	Low-Moderate

Six of the eight categories were deemed to have a moderate-high or high level of priority with three of those (materiel, personnel, and organization) having a grade of 4 or 5. The goal is to have the categories with higher priorities to have a higher grade. The three categories with lower grades (doctrine 1, training 3, leadership & education 3) all have priorities of high to moderate-high, thus they must be given the most attention to successfully move forward with UAV-USV teaming in the ISR-T arena.

Doctrine, training, and leadership & education were determined to be the three DOTMLPF-P categories needing the most attention before UAV-USV teaming in the ISR-T environment can move forward. First and foremost, relevant doctrine needs to be developed to include a concept of operations (CONOPS) and tactics, techniques, and procedures (TTPs). We recommend a joint UAV-USV teaming working group (WG) be established by Commander, Naval Forces and Commander, Naval Surface Forces to create related CONOPS and TTPs—as it was done with a CONOPS WG for large and medium USVs.

We recommend to continue to work UAV-USV teaming into naval exercises and events to include conducting this work with a carrier strike group in 2023 and beyond.

We recommend the Department of Defense pursue partnerships with civilian UAV developers to ensure US military UAVs remain competitively advantageous against adversaries. There is a wide array of UAV applications envisioned for the future that would benefit both the defense and civilian sectors.

We recommend leveraging advances in processing power so USVs can act as both a repository and dispenser of unmanned ISR-T data and to dynamically lower the communications grid to remain suitable in communications denied environments. Cloud processing capabilities could be incorporated as redundant or supplementary means of processing ISR-T in permissive environments. Onboard processing of unmanned systems could not only mitigate atmospheric and adversary-related vulnerabilities by deprecating dependency on satellite communications but also enhance the warfighting effectiveness of deployed strike groups by shifting the data processing capabilities from shore assets to the tactical edge.

In addition, LT Peter Winstead's 2018 thesis has several pertinent recommendations that are also included in our recommendations section.

Recommendations for Further Research

Additional research is recommended to study how to reduce the drag of fixed-wing hybrid vertical takeoff and landing unmanned aerial vehicles (UAVs) while improving mobility and flight endurance. Coupling the maneuverability of rotary aircraft with the range and endurance of fixed-winged aircraft could allow for the performance of complex intelligence, surveillance, reconnaissance, and target acquisition missions that other UAV configurations would not be able to conduct.

References

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NPS-22-N355-A: Distributed Maritime Logistics for Theater Undersea Warfare

Researcher(s): Shelley Gallup

Student Participation: No students participated in this research project.

Project Summary
Logistics has always been the means to victory or a primary factor in defeat. Logistics does not just happen but must be planned. A very close relationship exists between what is in the fight (the platform, weapon, technology, people) that generates needs and the ability to fulfill those needs. As we move from wars in the Middle East and start realizing the potential power and projection of peer competitors' national will, it becomes obvious that a shift in both force structure and means to support that force structure must change. Logistics are primary targets of adversaries, and thus the domain in which logistics activities occur is also a major consideration. In this research, we look specifically at the undersea domain. The undersea warfare environment is in a state of evolution towards unmanned and autonomous vehicles. Challenges to logistics are complex and include the development of how and when needs arise for different platforms doing myriad duties in undersea and seabed warfare. We are leaving the manned submarine component aside in this research to focus on this evolution. What the research seeks is an understanding of this new architecture in a framework like the internet of things. Thus, on one side is the complexity of the physical technologies in the water and on the other is the need to distinguish needs and support them in an optimized way, which is also related to the context of the conflict environment. This research is the continuation of a first year's effort seeking primary thinking and plans for distributed maritime operations (DMO) with undersea included. This year extends that effort to optimization of logistics in the oncoming new reality of undersea warfare. Deliverables include a technical report and possible solutions.

Keywords: *logistics, undersea logistics, seabed warfare logistics, autonomous undersea warfare, internet of things, distributed maritime operations, DMO*

Background
Transforming ways in which the navy will engage near-peer competitors in the grey zone and beyond has already begun. There is still work needed to obtain the right naval surface force structure, and that debate is ongoing. However, where there is little disagreement is in the oncoming future use of autonomous sensors. Many small things distributed widely versus a few big things that are visible and targetable is an obvious and practical choice. One dimension of warfare where this is becoming increasingly important is in the undersea domain. Undersea and seabed warfare have been under-appreciated in the past (excepting manned submarines) because the ocean is a very difficult environment in which to gather information

and get that data where it needs to go. This research explores the logistics problem of support to the "many small things" in undersea and seabed warfare from which huge amounts of valuable data can be drawn.

How should shortcomings in the current logistics design change to reflect today's realities while enabling the fight forward? Lacking in these discussions is the most overlooked area of conflict in this new peer competitive environment—undersea warfare. Undersea warfare is largely defined by the physics of the environment and its ability to cover over a lot of devices that are unseen and unheard, with a lot of mission variety.

It is very difficult to have a one model approach to seabed and undersea warfare. Equipment is optimized for its role. Communications are very difficult, exposure on the surface can be a problem, and they are likely to continue along a path of pure autonomy with little human interaction (excepting human-in-the-loop for prioritizing needs). This research details the common categories for two undersea systems that might need logistical planning. For example, energy needs will be different for an autonomous undersea vehicle looking for unique objects on the seafloor, than a wave-glider that is partially submerged and generates power from its wave action environment. Thus, a framework of vehicle type, mission and unique system needs on the x side of the matrix and the capabilities available to service needs on the y-axis produces a table in which we can put an "X" or an "O".

Nonetheless, this is only part of the story. Knowing the needs of these new devices must be meshed somehow with the availability of sustainment capabilities afloat and ashore. Moreover, there are mitigating circumstances for sustainment such as covertness, undersea or surface services, offload of data and uploading to a waiting subscriber, authorities that generate priorities supporting commander's intent, and more.

This is a complex mathematical problem, one that LCDR Stephen Cone characterizes as "capacitated team orienteering problem with time windows and synchronization" in his 2022 thesis. The thesis shows an optimization method to best route various medical evacuation assets in contested environments to casualties with various severities. Except in our case, we have different service vessels routing to various customers (sensors) with different needs and various time constraints.

As the second year of a two-year effort, this research will finalize "needs" vs. sustainment, with sustainment being divided into subsets of varying constraints as well. This problem will be considered in multiple scenarios using the mathematics of optimization. The result will be a much better idea of what is needed in the chief of naval operations' transformative vision.

Findings and Conclusions

Midway through the two-year problem we have identified different classes of undersea sensors and weapons that should be considered, as they are possible in the near term. Multiple concepts out to 2045 are not going to be included in this study. We advocate for the near terms as this will set a new evolutionary path for how to deal with a navy approach of "many things," versus that of a "few things." New ways of understanding the problem space are the primary objective of this research, and secondarily to re-focus on the intrinsic need to include undersea and seabed warfare in warfare at all phases. It is expected that as we clarify the current means for approaching this complex problem, it can be adapted further to include other systems of systems of the same logical type.

Recommendations for Further Research

Undoubtedly there will be follow-on research to advance and refine these optimization techniques and make them part of an artificial intelligence system that can build logistics and sustainment plans based on the current context and commander's intent. Eventually, the shore side of the problem would become less about planning and more about availability for what is needed. Logistics of the past simply will not work in our near-peer competitive and grey zone environment. At the same time, we push forward with autonomous systems that simply need to be provisioned for a logistics mission and then launched with its internal command and control already set.

References

Cone, S. (2022). *Casualty evacuation optimization in a conflicted environment* [Master's thesis, Naval Postgraduate School].

List of Abbreviations and Acronyms

2LT – 2nd Lieutenant
A2/AD – Anti-Access/Area Denial
AAAI – Association for the Advancement of Artificial Intelligence
AAR – Air-to-Air Refueling
ABMS – Advanced Battle Management System
ACM – Association for Computer Machinery
ADALM-PLUTO – Analog Devices Active Learning Module, PlutoSDR
ADS – Availability Duration Scorecards
AF – Air Force
AI – Artificial Intelligence
AIS – Automatic Identification System
Al-GNP – Aluminum Graphene Nano Platelets
AM – Additive Manufacturing
AOI – Area of Interest
AOR – Area of Responsibility
APL – Applied Physics Laboratory
AR – Augmented Reality
ARG – Amphibious Ready Groups
ASAT – Anti-Satellite
ASN(RDA) – Assistant Secretary of the Navy (Research, Development, and Acquisition)
ASONAM – Advances in Social Network Analysis and Mining
ASW – Anti-Submarine Warfare
AUV – Autonomous Undersea Vehicle, Autonomous Underwater Vehicle
AVN – Aviation
AVO – Air Vehicle Operator
AVO-UAS – Air Vehicle Operator, Unmanned Aircraft Systems
BA – Budget Activity
BGen – Brigadier General
BLOS – Beyond Line-of-Sight
BPC – Building Partner Capacity
BRI – Belt and Road Initiative
BUD/S – Basic Underwater Demolition/SEAL
C4ISRT – Command, Control, Communications, Computers, Intelligence, Survival, Reconnaissance, and Targeting
C5ISRT – Command, Control, Communications, Computers, Cyber, Intelligence, Survival, Reconnaissance, and Targeting
CA – Cognitive Assistance
CaaS – Communication-as-a-Service
CAC2S – Command & Control System
CAD – Computer-Aided Design
CANARY – Chemical/biological Agent Nuclear And Radiological Yield
CAPT – Captain
CBM+ – Condition-Based Maintenance Plus
CBRNE – Chemical, Biological, Radiological, Nuclear, and Explosive
CCM – Capability Costing Model
CCRP – Command and Control Research Portal
CD&I – Combat Development and Integration
CDC – Conference on Decision and Control
CDDs – Capability Development Documents
CDF – Cumulative Distribution Function
CDM – Conceptual Data Model
CDNI – Combat Development and Integration
CDR - Commander
CEC – Consumer Electronics Control
CGs – Guided-missile Cruisers
CISA – Cybersecurity & Infrastructure Security Agency
CIWS – Close-in-Weapon-System
CLF – Combat Logistics Force
CMOS – Complementary Metal-Oxide Semiconductor
CMS – Content Management Systems
CNBC – Consumer News and Business Channel

CNO – Chief of Naval Operations
CO – Commanding Officer
COA – Course of Action
COG – Cognizance Code
COI – Contact of Interest
COL – Colonel
COMMARFORCOM – Marine Corps Forces Command
CONOP – Concept of Operations
CONOPS – Concept of Operations
COP/CTP – Common Operating Picture/Common Tactical Picture
COTS – Commercial-off-the-Shelf
COVID – Corona Virus Disease
CPT – Captain
CPU – Central Processing Unit
CRISP-DM – Cross Industry Standard Process for Data Mining
CRS – Congressional Research Service
CSG – Carrier Strike Group
CUI – Controlled Unclassified Information
CUI/NOFORN – Controlled Unclassified Information, No Foreign Nationals
CVW – Carrier Air Wing
CW – Cogent Way
DARPA – Defense Advanced Research Projects Agency
DB – Database
DCI – Deputy Commandant Information
DDGs – Guided-missile Destroyers
DDIL – Denied, Degraded, Intermittent or Limited
DevSecOps – Development, Security, and Operations
DEW – Directed Energy Weapons
DFC – Development Finance Corporation
DIKUW – Data-Information-Knowledge-Understanding-Wisdom
DL – Deep Learning
DMO – Distributed Maritime Operations
DNN – Deep Neural Networks
DoD, DOD – Department of Defense
DOE – Design of Experiment
DoN, DON – Department of Navy
DOTMLPF-P – Doctrine, Organization, Training, Materiel, Leadership & Education, Personnel, Facilities, and Policy
DP – Design Point
EABO – Expeditionary Advance Base Operations
EDO – Engineering Duty Officer
ELECTRE – Elimination and Choice Expressing the Reality
EM – Electromagnetic
EMS – Electronic Magnetic Spectrum
ENS – Ensign
EOD – Explosive Ordnance Disposal
EP – Early Promote
EPF – Expeditionary Fast Transports
ERA – Entity, Relationship, Attribute
ESG – Expeditionary Strike Group
ESPDU – Entity State Protocol Data Unit
ESPM – End-Strength Planning Model
EUCOM – European Command
EVALs – Evaluations
EVE – Event-Verb-Event
EW – Electronic Warfare
FAB – Foundations and Applications of Big Data Analytics
FANET – Flying Ad Hoc Network
Fe_2O_3 – Iron(III) oxide, also known as rust
FeO – Iron (II) oxide
FITREPs – Fitness Reports
FLS – Forward-Looking Sonar
FOV – Field of View
FS – Forward Security
FSCU – Fire Support Coordination Unit
FUSED – Fuel Usage Study Extended Demonstration

List of Abbreviations and Acronyms Cont.

FVL – Future Vertical Lift
GAO – Government Accountability Office
GCS – Ground Control Station
GEO – Geosynchronous or Geostationary
GEOINT – Geospatial Intelligence
GHz – Gigahertz
GNP – Graphene Nanoplatelets
GPC – Great Power Competition
GPS – Global Positioning System
GRG – Generalized Reduced Gradient
HAB – High Altitude Balloon
HADR – Humanitarian Assistance And Disaster Relief
HDFS – Hadoop Distributed File System
HED – Hybrid Electric Drive
HEL – High Energy Laser
HMD – Head-Mounted Display
HMMWV – High Mobility Multipurpose Wheeled Vehicle, better known as the Humvee
HMT – Human-Machine Teaming
HPM – High-Power Microwave
HQMC – Headquarters Marine Corps
HRDP - Human Resources Development Process
HSR – Hierarchical Scoring-Ranking
HTML5 – Hypertext Markup Language 5
IA – Interdependence Analysis
IBS – Integrated Broadcast System
IC – Integrated Circuit
ICBM – Intercontinental Ballistic Missile
ICD – Initial capability document
ICOP – Intelligence Carry-on Program
ID – Identify
IED – Improvised Explosive Devices
IEEE – Institute of Electrical and Electronics Engineers
IFAC-PapersOnLine – International Federation of Automatic Control Open-Access Journal
IFC – Intermediate Force Capabilities
IHMC – Institute for Human & Machine Cognition
INDOPACOM – Indo-Pacific Command
IP – Internet Protocol
IPT – Integrated Product Team
IRB – Institutional Review Board
ISR – Intelligence, Surveillance, And Reconnaissance
ISR-T – Intelligence, Surveillance, Reconnaissance, and Target Acquisition
ISRT – Intelligence, Surveillance, Reconnaissance, and Targeting
IT – Information Technology
ITSEC – Interservice/Industry Training, Simulation, and Education Conference
IWC – International Whaling Commission
JADC2 – Joint All-Domain Command and Control
JCA – Joint Campaign Analysis
JCIDS – Joint Capabilities Integration and Development System
JIFCO – Joint Intermediate Force Capabilities Office
JIFX – Joint Interagency Field Experimentation
JLTV – Joint Light Tactical Vehicle
JP-5 – Kerosene-based fuel used in naval aircraft
JP-8 – Kerosene-based fuel used in naval aircraft
JPAAS – Joint Planning and After-Action System
JS – Joint Staff
JTF – Joint Task Force
KF – Kalman filter
KPP – Key Performance Parameter
KSA – Key-Systems Attribute
LAILOW – Leverage AI to Learn, Optimize, and Wargame
LCDR – Lieutenant Commander
LCS – Littoral Combat Ship
LED – Light Emitting Diode

LEO – Low-Earth Orbit
LLA – Lexical Link Analysis
LML – Lifecycle Modeling Language
LMP – Liquid Metal Printing
LOCE – Littoral Operations in a Contested Environment
LOE – Line of Effort
LPI/LPD – Low Probability of Intercept/Low Probability of Detection
LT – Lieutenant
LTJG – Lieutenant Junior Grade
M&RA – Manpower and Reserve Affairs
MACO – Master of Applied Cyber Operations
MAGTF – Marine Air-Ground Task Force
MAJ – Major
MANGL – Marine Air Ground Task Force Agile Network Gateway Link
MARCORSYSCOM – Marine Corps Systems Command
MARSOC – Marine Forces Special Operations Command
MARSOF – Marine Special Operations Forces
MATLAB – Matrix Laboratory, a multi-paradigm programming language and numeric computing environment
MBSE – Model-Based Systems Engineering
MCA – Multi-Criteria Analysis
MCDA – Multi-Criteria Decision Analysis
MCEN – Marine Corps Enterprise Network
MCM – Mine Countermeasures
MCO – Marine Corps Order
MCS – Monte Carlo Simulation
MCSC – Marine Corps Systems Command
MEDEVAC – Medical Evacuation
MEF – Marine Expeditionary Force
MIO – Maritime Interception Operations
MIS Quarterly – Management Information Systems Quarterly, a peer-reviewed academic journal
MIT – Massachusetts Institute of Technology
ML – Machine Learning
ML-KF – Machine Learning used in a Kalman filter system
MLG – Marine Logistics Group
MLGO – Marine Logistics Group Order
MLS – Messaging Layer Security
MOE – Measure of Effectiveness
MOOTW – Military Operations Other than War
MORFIUS – Mobile Radio Frequency-Integrated UAS Suppressor
MOS – Military Occupational Specialty
MOVES – Modeling, Virtual Environments, and Simulation
MP – Must Promote
MS – Microsoft
MS – Master of Science
MSL – Mean Sea Level
MTF – Medical Treatment Facility
MVP – Minimum Viable Product
NAILE – Networked Airborne ISR&T Long Endurance
NAILE-CA – Networked Airborne ISR&T Long Endurance - Communications Architecture
NASA – National Aeronautics and Space Administration
NATO – North Atlantic Treaty Organization
NAVAIR – Naval Air Systems Command
NAVEUR – US Naval Forces Europe
NAVPLAN – Navigation Plan
NAVSUP – Naval Supply Systems Command
NAVWAR – Naval Information Warfare Systems Command
NAWCWD – Naval Air Warfare Center Weapons Division
NC – Nuclear Command
NC2 – Nuclear Command and Control
NC3 – Nuclear Command, Control, and Communications

NCCM – Naval Counselor Master Chief Petty Officer
NDS – National Defense Strategy
NDSA – National Defense Space Architecture
NECC – Naval Expeditionary Combat Command
NECE – Navy Expeditionary Combat Enterprise
NEE – Named Entity Extraction
NFRS – Navy Force Review Study
NIIN – National Item Identification Number
NIST – National Institute of Standards and Technology
NIWC-PAC – Naval Information Warfare Center Pacific
NLP – Natural Language Processing
NMC – Non–Mission Capable
NOA – Naval Operational Architecture
NOVA – A model of Unmanned Aerial Vehicle
NPS – Naval Postgraduate School
NRP – Naval Research Program
NS3 – Network Simulator 3
NSN – National Stock Number
NSW – Naval Special Warfare
NTR – None To Report
NWSI – Naval Warfare Studies Institute
OccFld – Occupational Field
OCR – Optical Character Recognition
OFRP – Optimized Fleet Response Plan
OIE – Operations in the Information Environment
OLS – Ordinary Least Squares
OMB – Office of Management & Budget
OMNR – Operations and Maintenance Navy Reserve
OODA – Observe, Orient, Decide, and Act
OPD – Observability, Predictability, and Directability
OPNAV – Office of the Chief of Naval Operations
OPORD – Operational Order
ORD – Operational Requirements Document
OTH-Gold – Over the Horizon - Gold
P-LEO – Persistent Low-Earth Orbit
PACE – Primary, Alternate, Contingency, and Emergency
PBIS – Program Budget Information System
PCS – Post Compromise Security
PDF – Portable Document Format
PE – Program Element
PES – Performance Evaluation System
PETG – Polyethylene terephthalate glycol
PETG-GNP – Polyethylene terephthalate glycol with Graphene Nanoplatelets embedded in it
PI – Principal Investigator
PLA – People's Liberation Army
PLAN – People's Liberation Army Navy
pLEO – Proliferated Low-Earth Orbit
PMC – Partial–Mission Capable
PNF – Partner Nation Forces
POL – Petroleum, Oil, and Lubricant
POM – Program Objective Memorandum
POR – Program of Record
POS – Parts of Speech
POWER – Persistent Overwatch and Electronic Reconnaissance
PP&O – Plans, Policies & Operations
PPBE – Planning, Programming, Budgeting, and Execution
PRC – People's Republic of China
PROMETHEE – Preference Ranking Organization Methods for Enrichment Evaluations
RAS – Replenishment at Sea
RBD – Reliability Block Diagrams
RBS – Readiness-Based Sparing
RDML – Rear Admiral
RDT&E – Research, Development, Test, and Evaluation
RF – Radio Frequency

RHIB – Rigid Hull Inflatable Boat
RMC – Regional Maintenance Center
ROI – Return on Investment
ROV - Remotely Operated Vehicle
RSCA - Reporting Senior’s Cumulative Average
RST – Rich Semantic Track
SA – situation awareness
SAF/AQ – Secretary of the Air Force – Acquisition, Technology and Logistics
SAG – Surface Action Group
SAR – Synthetic Aperture Radar
SATCOM – Satellite Communications
SCAR – Strike Coordination and Reconnaissance
SD – Secure Digital
SDA – Space Development Agency
SDR – Software-Defined Radio
SEAL – Sea, Air, and Land
SEED – Simulation Experiments & Efficient Designs
SEM – Scanning Electron Microscope
SiC – Silicon carbide
SLD – Strategic Laydown and Dispersal
SMART-T – Secure, Mobile, Anti-Jam, Reliable, Tactical Terminal
SME – Subject Matter Expert
SMWDC-MIW – Surface and Mine Warfighting Development Center Mine Warfare Division
SNA – Semantic Network Analysis
SOF – Special Operations Forces
SOF-MAGTF – Special Operations Forces, Marine Air Ground Task Force
SOP – Standard Operating Procedure
SORG – Submarine Operations Research Group
SoS – System of Systems
SOTF – Special Operations Task Force
SQL – Structured Query Language
SSAG – Space Systems Academic Group
SSBN – Ballistic Missile Submarine
SSR – Strategic Shaping and Reconnaissance
STITCHES – System-of-systems Technology Integration Tool Chain for Heterogeneous Electronic Systems
STK – Systems Tool Kit
STORM – Synthetic Theater Operations Research Model
sUAS – Small Unmanned Aircraft Systems
SUPSHIP – Supervisor of Shipbuilding
SWaP – Size, Weight, and Power
SWRMC – Southwest Regional Maintenance Center
SYSCOM – Systems Command
TASOM – Torpedo Allocation Stochastic Optimization Model
TCPED – Tasking, Collection, Processing, Exploitation, and Dissemination
TF-IDF – Term Frequency-Inverse Document Frequency
TFDW – Total Force Data Warehouse
TFF – Total Force Fitness
TFPM – Total Force Planning Model
TLS – Transport Layer Security
TPFDD – Time Phased Force Deployment Data
TTPs – Tactics, Techniques, and Procedures
TVS – Trait Validation System
U.S. – United States
U.S.S. – United States Ship
UAE – United Arab Emirates
UAH – Up-Armored HMMWV
UAS – Unmanned Aircraft System
UAV – Unmanned Aerial Vehicle
UCAV – Unmanned Combat Aircraft Vehicle
UCS – Union of Concerned Scientists
UHTC – Ultrahigh Temperature Ceramics
UN – United Nations
URL – Unrestricted Line
US – United States
USA – United States of America
USAF – United States Air Force

USCENTCOM – United States Central Command
USCG – United States Coast Guard
USENIX – an American nonprofit that supports advanced computing systems, operating systems, and computer networking research
USEUCOM – United States European Command
USFF – US Fleet Forces Command
USINDOPACOM – United States Indo-Pacific Command
USMC – United States Marine Corps
USN – United States Navy
USNI – United States Naval Institute
USNWC – United States Naval War College
USS – United States Ship
USSR – Union of Soviet Socialist Republics
USSTRATCOM – US Strategic Command
USV – Unmanned Surface Vehicles
USW – Undersea Warfare
UUV – Unmanned Undersea Vehicle
UV – Ultraviolet
UV-B – Ultraviolet B
UxV – Unmanned Vehicle
VADM – Vice Admiral
VBA – Visual Basic for Applications
VBSS – Visit, Board, Search, and Seizure
VHF – Very-High Frequency
VR – Virtual Reality
VTOL – Vertical Takeoff and Landing
WG – Working Group
WIC – Warfare Innovation Continuum
WiFi – Wireless Fidelity
XRD – X-ray Powder Diffraction
ZrB_2 – Zirconium diboride
ZrO_2 – Zirconium dioxide