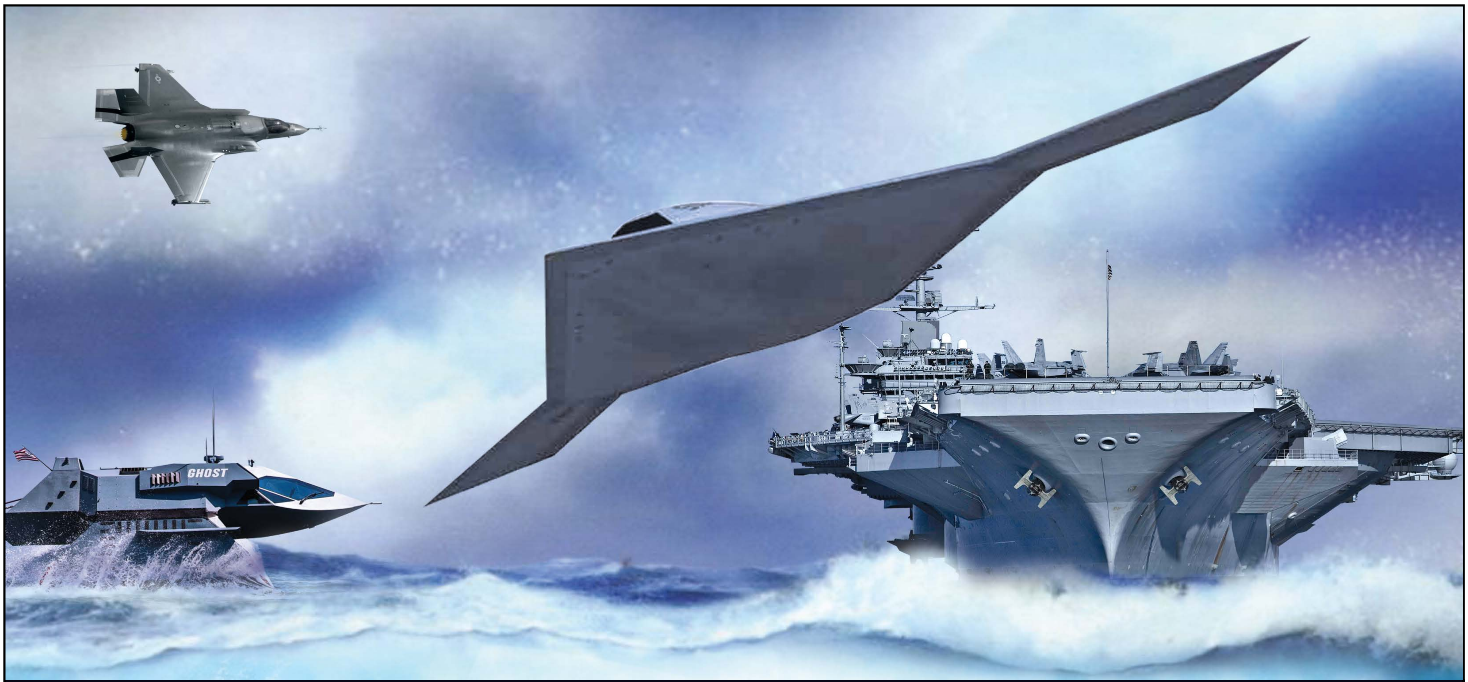

NAVAL RESEARCH PROGRAM

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NAVAL RESEARCH PROGRAM · NAVAL POSTGRADUATE SCHOOL

2018 ANNUAL REPORT

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NAVAL RESEARCH PROGRAM

NAVAL POSTGRADUATE SCHOOL

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MESSAGE FROM THE DEAN OF RESEARCH

I am pleased to support the Naval Postgraduate School (NPS) Naval Research Program (NRP) in the fifth complete fiscal year of the program. The studies sponsored within FY18 have made significant contributions to the Department of the Navy (DoN) by providing insights to key operational decision-makers along with recommendations to support cost savings in a fiscally constrained environment. The NRP's funding and program goals are directly in line with SECNAV's goal to provide research to "support[s] the Navy in reaching well-informed, objective decisions on strategic, operational, and programmatic issues through collaborative research."

This report highlights results from the spectrum of NPS NRP research activities conducted on behalf of both Navy and Marine Corps Topic Sponsors during the 2018 fiscal year. Executive summaries from the research projects are included in the report. While most of those summaries detail final results, some projects have multi-year project lengths. In those cases, progress-to-date is reported.

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

Looking forward to the current fiscal year, NRP is enjoying its first full year under the direction of its civilian program manager, Mr. Matt Kline as well as being a recognized component within the Navy Analytic Office (NAO). As part of the NAO portfolio, NPS faculty and students are uniquely empowered to learn from and contribute to Naval problem sets at the highest levels.

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

Dr. Jeffrey Paduan NPS Dean of Research

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Naval Research Program Overview

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

Background

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

Organization

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

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

Mission and Goals

The NPS NRP mission is to: Provide operationally relevant research experiences to NPS faculty members, provide operationally relevant thesis opportunities to NPS students, and provide useful results from research projects and studies to topic sponsors across the naval enterprise and in coordination with the Navy Analytic Office (NAO). The goals of the NPS NRP are to:

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

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

Program Administration

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

Accomplishments

The NPS NRP represents a strategic statement about the tangible and intangible value that NPS provides the entire naval community. It has proven to be a significant integration vehicle for partnering naval sponsors and NPS researchers to deliver cost-efficient results. The NRWG is one manifestation of this integration process. More than 50 Navy and Marine Corps organizations throughout the naval community have actively supported opportunities to engage NPS faculty and students through participation in the NRWG event. To date, the NRP has collected over 2,000 potential and current research topics through NRWG events, while funding over 350 research projects. Embedding the NRP into the fabric of the NPS strategic planning process enables the school to rapidly respond to current and future "compass swings" in naval research requirements.

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

- In FY18, $11.2M, in funding distributed, which translated into over 78 distinct U.S. Navy and Marine Corps projects that cover the entire Office of the Chief of Naval Operations (OPNAV) staff, Fleet Forces (FF), Assistant Secretary of the Navy for Research, Development and Acquisition (ASN (RDA)), Strategic Systems Programs (SSP) and Marine Corps functional organizations.
- The NRP has mobilized the NPS faculty to focus more of their research on naval issues. To date, over 300 faculty and military faculty from all four academic schools have joined the NRP effort, highlighting NPS' campus-wide commitment to naval research.
- Cross-campus, inter-departmental research partnerships represent over a quarter of the projects. They provide an advantage from the application of integrated perspectives and resulting multidisciplinary approaches.
- The NRP enjoys robust student engagement, leveraging the students' previous operational experience and newfound knowledge from graduate studies. There were over 170 United States and foreign thesis students collaborating with faculty on 60 of the 78 projects.

FY18 Research Highlights

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

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

Data Science and Machine Learning

The Naval Research Program funded studies related to data science and machine learning. Some studies, such as NPS-18-N081-A: The Implications of Co-Active Design on Manned Unmanned Teaming in Naval UxS Operations and NPS-18-N013-A: Reinforcement Learning for Modeling Large Scale Cognitive Reasoning (Phase II), focused on the algorithms and logic behind machine learning. Other studies, such as NPS-18-N185-A: An End-to-End Big Data Application Architecture for the Common Tactical Picture and NPS-18-M319-A: Improving Marine Corps Logistics with Model-driven Big Data focused on the adoption of big data and machine learning into the Navy. The breadth of topics leveraging big data and machine learning span all of the warfare domains from air to cyber to undersea. The studies also highlight the impact data science and machine learning will have on challenges such as insider threat, additive manufacturing, and sonar detection. Individually, the studies provide answers to the specific questions or the Topic Sponsors. In aggregate, they are building the capacity of NPS to respond to the challenges of adopting artificial intelligence across the Department of Navy.

Innovation

In line with the broader focus on innovation, the Naval Research Program delivered in key areas. Innovation is the adoption of a new practice within a community. Several studies focused on understanding innovation within specific communities in the Navy and best practices for adopting innovations in those communities. Some studies that highlight that theme include: NPS-18-N190-A: Implementing the DoN 30-Year R&D Plan: Creating a Culture That Values Learning, Collaboration and Innovations. Other studies looked at the adoption of key technologies across differing disciplines. Studies that highlight this theme include: NPS-18-N014-A: Unmanned Surface Logistics Concept of Support and NPS-18-N386-A: Culture Change and Modernizing Navy Logistics.

Cyber

In Cyber, the studies provided tailored answers to the challenges facing the naval service from sustaining operations at sea (NPS-18-N355-A: Additive Manufacturing in Naval Domain: Innovation, Adoption and Taxonomy of Cybersecurity Threats). A newly developed and applied, methodology for understanding the needs and performance of networks was the focus of NPS-18-N196-A: Future Combat Systems – Data and Information Science Technologies as a Force Multiplier. More broadly, these FY18 research projects, NPS-18-N094-A: Cognitive Threat Emitter Recognition of Behaviors with Deep Neural Networks and NPS-18-N196-A: Future Combat Systems – Data and Information Science Technologies as a Force Multiplier, underscore that Cyber is the critical enabler for all of the other systems in other domains to operate effectively.

Talent Management

Talent management studies highlighted that the common concerns shared by the Navy and the Marine Corps often require solutions tailored to the specific culture of each service. Both the Navy and Marine Corps were concerned about talent management, but each approached the topic differently. For the Navy, the issue was captured in the study NPS-18-N320-A: Improving Visibility of Talent: Analysis of Technical Skills and Cognitive Aptitude of Navy Officers. For the Marine Corps, NPS-18-M222-A: Intangible Benefits in the Composition of the Marine Corps approached the talent management question from an optimization aspect, seeking to provide a framework to help determine the "optimal" number of women in the Marine Corps. Both services are interested in non-cognitive measures and retention analysis models.

Acquisition and Logistics

The NRP supports the core service function of equipping the force. In acquisitions, this was highlighted by the research into full ship shock testing in NPS-18-N393-A: Development of Shipboard Equipment Shock Survivability Assessment Technique. Other studies investigated the opportunities offered by emerging technologies such as NPS-18-N014-A: Unmanned Surface Logistics Concept of Support and NPS-18-N116-A: Expeditionary Logistics: A low-cost, Large-scale, Unmanned, Deployable Sensor Network to Support Airfield/Pier Area Damage Assessment. Much of the research for naval logistics focused on fuel consumption, planning, and resource allocation. This research is represented by NPS-18-N038-A: Multi-Commodity Push/Pull Logistics for Distributed Lethality. NRP studies provide the analytical foundation for decision makers and planners to optimize what is acquired and how it is supported.

Global Strategy

The National Defense Strategy signed in 2018 focuses on the return of strategic competition and its impact on U.S. strategy. The FY18 research aligned with the National Defense Strategy. NRP projects such as NPS-18-N376-A: Naval and Maritime Strategy address the relationship between high-level national strategy and the Navy's role in crafting a maritime strategy to meet national-level objectives, while NPS-18-N251-A: Limited Nuclear Conflict focused on the threat from Russia. Other studies focused on broader themes such as conducting a social network analysis of the maritime logistics network in Western Pacific (NPS-18-N077-A: Hiding in Plain Sight: Logistics in WestPac). Several studies highlighted the need for increased awareness and mitigation of access for intelligence, surveillance, and reconnaissance (ISR) in the Maritime Domain, (NPS-18-N264-A: GEOINT Small Satellite Constellation Study for Maritime Domain Awareness and NPS-18-N300-A: Unclassified Maritime Domain Awareness). All of these studies focus on naval responses in support of the National Defense Strategy.

NPS-18-N081-A: The Implications of Co-Active Design on Manned Unmanned Teaming in Naval UxS Operations

Researcher(s): Dr. Dan Boger, CAPT Scot Miller USN Ret., Dr. Arkady Godin, Ms. Ann Gallenson, and CDR Sue Higgins USN Ret.
Student Participation: Capt Yusef Akbarat USMC, LtCol Alan Clarke USMC, Maj Dan Knudsen USMC, Capt Lorenso Trevino USMC, and Maj Steve Harvey USMC

Project Summary

Unmanned systems offer the Department of Defense (DoD) the chance for non-humans entities to take on the dull, dirty, and dangerous tasks often assigned to DoD. Current approaches to leveraging these emerging capabilities tend to drive towards unmanned system that are "autonomous". However, the term autonomy is misunderstood and poorly defined. We propose the word *automated* for those particular tasks that the unmanned vehicle can perform itself with reliability.

Research of various articles on DoD unmanned operations suggest that many within DoD believe that fully automated unmanned systems, those that are "fully autonomous", are the Holy Grail of robot performance. We propose that there is a higher level of human robot interaction, called interdependence, whereby humans and machines work collaboratively on a set of measurable goals, adjusting their efforts as the situation and environment change. Further, we believe that artificial intelligence (AI) efforts also have similar manned-unmanned teaming challenges and opportunities. For instance, some AI-based applications monitor human endeavors, and based on their algorithms and learning techniques, are designed to "collaborate" with the humans to achieve common goals. This is identical to the interdependence mentioned above, even though in the case of these AI applications the "robot" does not move.

Interdependence is achieved simply be executing three dynamic and continuous tasks between human and machine: observing, predicting, and directing (OPD). While simple in concept, considering these three interactions for every elemental task that exists in a collaborative operating environment is surprisingly complex. Co-Active Design was formulated to assist with this analytical process.

The rest of the paper describes the existing challenges, the Co-Active Design process, and several examples explored by the researchers on how Co-Active Design yields potential military benefits. We explain several of the challenges involved, and finish with the implications of Co-Active Design in support of various manned-unmanned teaming possibilities.

Keywords: *manned unmanned teaming, interdependence analysis, observability, predictability, directability*

Background

Imagine a Marine tele-operates a robot that has both movement and sensors. Because of the interface design, the Marine must focus solely on movement, while a second Marine operates the sensor. The two Marines must collaborate to best employ the robot. Because of the dynamic nature of the robot's use, this collaboration requires significant attention and interactions, since robot movement and location influence sensor performance. Often, the first Marine wants to keep the robot partially hidden, yet the sensor operator may achieve best sensor performance by having the robot in the open. Because of this deep attention, neither Marine can successfully defend themselves, since robot, operation demands their full attention. Thus a third Marine is assigned to defend the first two Marines. Often the sensor feed, and not actually protecting anyone transfixes that Marine. Marine Corps leaders may wonder if the loss of three armed Marines is worth the benefit of potentially improved sensing.

Consider the same operation with a fully autonomous robot. Marines would somehow prep the robot with the mission. The robot would proceed to the operating area and send the sensor data back to the Marines. This frees up at least one of the Marines. However, as soon as the mission changes, the environment changes, or the robot encounters problems, the Marines are exactly back to where they started. This scenario is not practical, since as is said, “No plan survives first contact with (anything).”

Consider a more complicated mission where direct interaction with the enemy, or even neutrals, is possible. Building a fully autonomous robot becomes increasingly complex. Almost every contingency must be engineered into the robot, making the cost increasingly prohibitive.
One might argue that Global Hawk is a purely autonomous unmanned vehicle, since it takes off and lands by itself. Yes, it does, but a human monitors every action, and the Global Hawk has a complete set of sensor operators.

Employing Co-Active Design to create interdependence, if performed correctly, allows developers to design robots that can do what robots do best, and rely on humans to do what they do best.

<u>Co-Active Design</u>
Co-Active design takes several steps. Tasks, subtasks, and required capacities is engineering-speak for describing the exact details needed to execute any given mission. One should expect this list to be quite extensive. Once that list is established, the rest of the columns support an analysis of how robots and humans will interact called an interdependence analysis (IA). The outputs of an IA are OPD requirements that are added to a column further to the right.

Notice that there are two alternatives for executing each task element. Normally, in the first alternative, the robot is the performer, and humans are the supporting team members. In alternative two, the human is the performer, and the robot provides support. In a team with multiple performers, such as a Marine Corps fire team, there may be additional performers, both robot or human. The bad news is that this can get very complex rapidly. The good news is that most of the analysis is the same for many of those possibilities. Note that most tactical units, where a collaborative robot might be employed, have relatively small elemental teams. A Marine Corp fire team has four members. Most tactical jet aircrews have two or less. Even on large platforms, which may have 11 crewmembers, can be reduced because of overlapping crew roles, to five.

Once the alternatives are established, IA enables users to analyze the ability of both the performer to do the task and of the supporting agent(s) to support the task. The analysis results in colors being put into each block.

If the robot can perform every single task, then that is an autonomous robot. However, note that its efficiency in doing the tasks can still be improved through assistance from supporting team members. In the real world, though, there are many elemental tasks that a robot or unmanned system can perform, but 1) not reliably, 2) it may need direct help, or 3) it will never be able to perform. This is where the analysis becomes interesting.

By studying and considering the task, what the robot might be able to do, and what the human team member might provide, one has to think about the OPD interactions for that task. Those become well-defined engineering requirements.

Then each of the other alternatives must be analyzed and the requirements derived. The good news is that many of the solutions for the various OPD requirements can be reused. The designer of this entire IA process is currently working on tools that can help to automate much of this analysis.

Discussions with practitioners of formal systems modeling, like those who use Object Management Group standard tools, believe that using the automated IA tool can be easily incorporated into their modeling framework. While IA is very complicated, much of the same work would be required anyway for teleoperated or autonomous systems. The use of an automated tool and formal models means that the entire IA can be easily verified and validated through parametric modeling or application of the solution into a virtual environment. For instance, other Naval Postgraduate School (NPS) researchers are already working on a virtual ground environment to evaluate Marine-machine teaming.

The usefulness of an IA does not stop here. After each task in an IA is considered for efficiency and reliability, the next steps in IA are to analyze whether the whole system is efficient and reliable; this involves a two-step process. The first is simply to trace the mission path through the IA. This simple effort reveals where tasks may not be reliably performed and thus may require additional requirements and attention. This process also reveals multiple paths for completing the mission, meaning that the analysts reveal ways to create mission reliability.
The second step is called planning for failure. Here a red team thinks of every possible way that the task can run into problems as well as what the alternative mission paths might be to complete the mission. While arduous, this process identifies more engineering, training, maintenance, and operating requirements. Because the red team, using experienced analysts, includes potential operators, they can be sure that every eventuality was considered. Consider that this red teaming is a key part of the design-for-trust approach.

Examples of Application

We offer three real life and proposed usage examples of IA next.
For one effort, NPS faculty and students worked with engineers to conduct IA in support of a subset of a Marine-machine fire team project. In this, a robot would replace the role of the assistant automatic rifleman (AAR) in a Marine Corps fire team. Two tasks were essential for the robot to participate: being able to move in a column with the Marine team and being able to move in a wedge formation with the team. Two implied tasks were also derived: shift from a column to a wedge formation and shift back.

To summarize, what seemed like four easily understood and distinct tasks evolved into nearly 100 subtasks. Engineers asked obvious questions, such as, “what is the spacing?” and “what is the bearing relative to the formation movement”? This led to questions about spacing requirements based on environment. Then it became obvious that when the formation shift was made, how does the robot avoid running into a teammate? That led to questions about how does the robot know where the teammate is? Since Marine Corps fire teams attempt to evade detection, resolving answers to these questions was quite difficult.

Several lessons emerge from this experience. First, creating manned-unmanned teaming is hard work. One cannot assume anything. Building reliability means that different communications paths are necessary, since the mission and the environment dictate various approaches. It seems overwhelming to think that the Marines could build a robot capable of serving as the assistant automatic rifleman. There are over 20 immediate action drills that such an entity should be able to perform almost reflexively.

The good news is that formal modeling supported this endeavor. All the behaviors that were analyzed are easy to reuse. Therefore, over time, capability might increase exponentially, meaning that the Marines not only would be able to create a robot to serve as an AAR on a fire team, but for many other roles.

The next example is that of the Navy's new Triton RQ-4C unmanned aircraft. The Triton is designed to provide long duration surveillance at altitude with a variety of sensors. The concept of employment is simple: employ the same crew used for manned flights and just house them at a base, evaluating the sensor feeds and ensuring that the aircraft flies in the right places. Because of the advanced new sensors though, it is estimated that the aircraft may detect over 48,000 contacts within its flight time. Assume the aircraft is on station for 20 hours. That implies 2,400 contacts per hour, 40 per minute, so nearly one contact per second. Discussions with the crews indicate that keeping up with such a deluge is not possible. In our research, we encountered a new system that uses machine learning to rapidly identify, classify, and sometimes even identify surface contacts. Imagine that tool being used to automatically evaluate the vast majority of contacts (since most are not of tactical value) and alerting the crew when a contact met crew-defined criteria of interest. This is another manned-unmanned teaming challenge. Again, an IA analysis needs to be performed to figure out how to best do this. The point is that while we are not using manned-unmanned teaming for the entire Triton mission set, we are working to modify one of the behaviors to make the process more effective and efficient. Manned-unmanned teaming can work in just a portion of the operating regime.

The final example involves a proposed warfighting decision aid. Imagine the aid is absorbing intelligence, surveillance, and reconnaissance and command and control feeds, including various enablers and influencers (weather, jamming, electronic warfare maneuver, etc.), creating weapon-target pairs and feeding platforms with new target sets, all dynamically. Whether this planned tool will actually do, anything remains to be seen. It will use a variety of machine learning and AI techniques. Both machine learning and AI tools need feedback loops to "learn" and improve. Such an aid also must communicate its results to operators for decision considerations and execution monitoring.

It is hard to imagine this decision aid being useful without careful consideration of manned-unmanned teaming, where the decision aid is the unmanned system. While it does not "move" like a robot, it is doing a lot of work that can help make decision makers more effective. However, it also must be monitored so that its machine learning internals do not get unbalanced and give wrong recommendations. Showing why it came up with recommendations will be necessary. It is a daunting challenge, but the payoffs can be huge. Imagine a war fighting decision aid that can monitor all inputs nearly simultaneously, plan for targets, and update constantly as it games possible enemy courses of action. The take away is that not all unmanned systems move, but Co-Active Design can still benefit the manned-unmanned relationship.

Concerns

Researchers working with the Marine Corps Warfighting Laboratory encountered suspicion of Marine-machine teaming as a valuable capability: "Is the manned unmanned teaming capability value added?"

It is not hard to see why. The above example of a robot moving information makes the simplest tasks seem quite complex. There is not enough real evidence of manned-machine teaming to actually validate our hypothesis. Yet we argue that the long-term future looks quite bright: when seen from the perspective of a technically savvy user, just 18 years ago most people were buying their first cellphones and learning to text. Given the growth in capability of a phone, why won't Marines be able to team with robots in the future?

In addition, can Marines, or any other DoD service, afford to not use machines to help in the future. Potential advisories are working on many varieties of unmanned systems. It would make sense to strive to achieve advanced machines that work to be good teammates. Machines can handle data much faster, and all the services are experiencing data avalanches with their new sensors. All the services are on the AI bandwagon, seeking new and varied uses for these tools. How can operators keep control of these devices without them behaving as collaborative teammates?

Findings and Conclusions

The world is changing. Data is king. Interesting uses of algorithms and AI are exploding. The ability to have unmanned systems do more is increasing. Most robot researchers drive tirelessly to building "autonomous" unmanned systems. Where does this stop? Today it still seems like fiction to consider robots taking over the world, but autonomous robots combined with machine learning-based self-learning algorithms seems scary. What could go wrong?

We believe a new model is needed now, one based on interdependence of unmanned systems and men working collaboratively together, leveraging what machines do best with what men do best. We believe that interdependence can benefit man in many ways, from just a part of automated computers tasks to the whole mission thread. We think this applies to robots that walk, fly, and swim, and those that operate in space, other planets, the moon, and even those that do not move at all.

Co-Active Design provides a comprehensive and logical approach to identifying the requirements to achieve interdependence, and it is just an extension of well-understood engineering principles. Interdependence is a simple but powerful tool, consisting of just three components, OPD. Co-Active Design and IA provide a comprehensive understanding of human machine interactions. It also provides for engineering reliability, effectiveness, efficiency, and resiliency into a system. Finally, Co-Active Design forces designers to consider and plan for failure, since planning to fail is better than failing to plan! Legitimate concerns about the value of interdependence exist. What is the value of a collaborative manned-unmanned team? Is it worth the investment, since Co-Active Design seems daunting and time consuming?

We agree more needs to be learned and done to ensure Co-Active Design success. Further research needs to develop the appropriate metrics for interdependence and co-Active Design. More exploration needs to be developed on the trust issues for manned-unmanned teaming. The Marine Corps work suggested that more work on manned-unmanned interface approaches is needed. This implies more consultation with the human factors community. The Coactive Design is logical and executable. However, there are many opportunities to add tools that would help expedite that process and promote reuse.

In the end, though, with the explosion of data, AI, various robots, and ethical employment situations, we argue that now is the time to adopt interdependence as our driving goal for manned-unmanned interaction, not autonomy. We believe the autonomy word should be banished, because it is so misunderstood and misused. Replace it with automation. We certainly want robots to strive to be able to execute certain actions automatically. We believe interdependence does need to apply immediately to all machines and men, but can be built slowly over time.

Recommendations for Further Research

With all this in mind, we recommend DoD proceed as follows:

- Reject autonomy and redefine all unmanned systems terms
- Make achieving interdependence a DoD policy. Establish an interdependence Key Performance Parameter
- Create metrics for interdependence and Co-Active Design
- Insist that practitioners of Co-Active Design use formal modeling methods to promote reuse, ease of test, information security, semantic interoperability, and other benefits

- Coactive Design needs a more comprehensive set of tools to automate IA, reliability, resiliency, and failure analyses
- Explore trust and ethics in interdependence
- Develop virtual environments for modeling interdependence and supporting IA
- Conduct manpower analysis about interdependence ramifications
- Examine the organizational challenges that come with executing the above recommendations. Consider establishing a fully resourced Interdependence Czar for the services, similar to what the Navy did with RADM Moffett and naval aviation, Admiral Rickover and nuclear power, and RADM Meyer and Aegis.

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NPS-18-N084-A: MEMS Direction Finding Acoustic Sensor

Researcher(s): Dr. Gamani Karunasiri, and Dr. Fabio Alves
Student Participation: LT Joshua Collins USN, and LCDR German Da Re ARA

Project Summary

The objective of the proposed two-year research program is to explore the possibility of developing direction finding acoustic sensors based on the ears of the fly *Ormia ochracea* for air and underwater applications. The ears of the fly are separated by less than a millimeter yet it has remarkable sensitivity to direction of sound. A typical sensor consists of two wings that are coupled in the middle and connected to the substrate using two torsional legs. The sensors were fabricated using micro-electro-mechanical system (MEMS) technology. The vibrations of the wings under sound excitation were probed using comb finger capacitors attached to the edges of the wings. The sensor response showed cosine dependence to incident direction of sound with very high sensitivity. The cosine dependence is due to interaction of sound from both front and back sides of the wings. A sensor assembly consisting of two sensors was used to unambiguously determine the direction. Field testing carried out at Camp Roberts showed that the sensor can determine the direction of sound within two degrees similar to that of the fly. For underwater applications, a new set of sensors were developed, and preliminary measurements showed that they operated as expected with good directional sensitivity.

Keywords: *directional, sound, sensor, MEMS, underwater, acoustic*

Background

The ability to find the direction of a sound source arises from the different distances sound travelled to each ear resulting in a phase difference, analogous to an amplitude difference for periodic sound waves. In animals with a relatively large ear separation compared to sound wavelength, the delay of the sound arrival and variation in the pressure field between ears allow for direction finding. Humans use this principle to determine sound direction with up to 2 degrees accuracy. However, there are insects such as the parasitic fly *Ormia Ochracea* with much smaller separation of ears that have developed a unique approach to direction finding. The female of this species seeks out chirping crickets to lay their eggs on, and do so with an accuracy of less than 2 degrees. The two eardrums of the fly are separated by a mere 0.5 mm, yet it homes in on the cricket chirping with a nearly two orders of magnitude longer wavelength.

The previous studies of a fly's hearing system [1] found that the two ear drums are mechanically coupled and have two normal modes that correspond to the eardrums moving in phase and out of phase. These modes, caused by the mechanical link between eardrums, give the *Ormia Ochracea* remarkable sensitivity to the direction of an incident sound stimulus. The fly employs the coupling between the two modes at the chirp frequency of a cricket to sense the direction, making use of the unequal vibrational amplitudes of the two eardrums.

Findings and Conclusions

During the course of research, MEMS directional sound sensors operating in air were designed based on an operation principle of the fly's hearing organ. The sensor consists of two wings (1x1 mm^2 each) made of 25 μm thick Si layers that are coupled in the middle and connected to the substrate using two torsional legs. The vibrations of the wings under sound excitation were probed using comb finger capacitors at the edges of the wings [2, 3]. The sensor response was found to have a cosine dependence with the incident angle due to the interaction of sound from both the front and back sides of the wings. The cosine dependence gives a symmetric response around the normal incidence which makes the determination of bearing ambiguous. For unambiguous determination of direction of sound, a dual sensor assembly was designed [4] to mount the sensors at a canted angle ($\theta_{off} = 30°$).

In order to remove the unknown sound pressure at the sensor assembly, the difference over sum ratio was calculated using the data which has a tangent dependence with incident angle [4]. This allowed us to unambiguously determine the direction of arrival of sound. Testing of the two-sensor assembly was carried out at Camp Roberts in California. The signals from both sensors were recorded and processed to determine the direction of sound as described earlier. Measurements were taken at 15° intervals over the range of ±60° using a sound source located at about 165 meters from the sensor. The peak responses of the two sensors was computed by the data acquisition system, and the difference over the sum at each of the angles was calculated to determine the measured angle. The measured vs actual angles were found to follow the ideal response line with a 45° slope. The average deviation between the measured and actual angles was found to be about 2^o close to that of the fly's hearing system. The sensitivity of the sensor was found to be about 10 V/Pa.

In addition to sensors operating in air, a new set of sensors were designed to operate underwater. For underwater operation, the sensors need to be immersed in a fluid with matching acoustic impedance to that of the water. For properly taking into account the interaction of the sensor with fluid, a new modeling technique was developed using a thermoviscous acoustic (TA) module of the COMSOL finite element modeling software. The sensor consists of a single 3 mm wide and 4 mm long cone shaped wing made of 25 μm thick Si layer where the narrow end of the wing is connected to the substrate. The larger wing area is needed for underwater detection of sound due to longer wavelengths involved which forced us to use a single wing to meet the design rules.

Measurement of the frequency and directional responses of the sensor underwater was performed at the Transducer Evaluation Center (TRANSDEC), an underwater characterization facility in San Diego. For underwater characterization sensor was packaged using a custom built housing with materials and fluid (silicone oil) to match the acoustic impedance of the water.
The measured frequency response was found to agree well with that of the simulations. The frequency response showed a resonant peak near 130 Hz which agrees reasonably well with that of the simulations using the thermoviscous acoustic module of COMSOL. The directional response of the sensor was also measured by rotating the sensor on its axis, and data showed the expected cardioid pattern indicating excellent directional sensitivity.

A feasibility study of miniature acoustic directional sensors operating in air and underwater with high accuracy directly addressed the requirements specified by the sponsor. The compact size and low power requirements could be helpful for applications in different operating environments. The participating student incorporated the results of that research in the thesis.

Recommendations for Further Research

For sensors operating in air, continued field testing is needed for determining the maximum range of detection as well as the possibility of identifying sound sources using their acoustic signatures. For sensors operating underwater, it is necessary to optimize their sensitivity by further refining the design based on the initial measurements. In addition, tunability of sensor response for different frequency bands of interest needs to be explored.

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NPS-18-N190-A: Implementing the DoN 30-Year R&D Plan: Creating a Culture That Values Learning, Collaboration and Innovation

Researcher(s): CDR Sue Higgins USN Ret., Dr. Don Brutzman, Ms. Ann Gallenson, Dr. Gail F. Thomas, and Dr. Rebecca Law

Student Participation: No students participated in this research project.

Project Summary

Navy leaders are concerned about the impact of accelerating rates of change on the Navy's effectiveness. They want to foster a culture of learning, collaboration, and innovation to increase lethality. The Department of Navy's (DoN) Thirty Year R&D Plan proposes a strategy to increase our technological advantage & maritime superiority in an increasingly dynamic security environment. The Naval Research and Development (R&D) Enterprise (NRDE) is integral to expanding the Navy's technical capability and assuring military advantages now and in the future.

We hypothesize that optimally positioned communities of interest (COIs) can act as a driving force in accelerating organizational culture change. We explored enabling factors to produce collaboration-based culture change and provided recommendations to improve the implementation of the R&D Plan.

We developed practices to catalyze COI efforts to implement the R&D Plan as we explored ways leaders can implement a long-term strategy by fomenting and sustaining organizational culture change. We focused on discovery, discussion, fostering collaboration, and building connections across naval institutions.

We concluded that changing culture requires aligning aspects of an organization to create an internal environment conducive to the desired changes. Leaders need to communicate the desired change and model the behaviors they want to instill. Creating a cross-organizational community requires cultivating opportunities that build interest, participation, and reward engagement in order to attract and retain participants. Communication platforms, forums, and educational opportunities need to be available to the COI. Informal systems require compatible rewards, often intrinsic, that enable people to be active participants who can promote and take pride in the desired changes.

Keywords: *DON 30 Year R&D Plan, culture change, agility, innovation, strategy, collaboration, community of interest*

Background

We use the following theory-based definitions to inform our work:

- Culture – "The set of assumptions (often unstated) that the members of a community have in common." (Sathe, 1985);
- Innovation – "Adoption of a new practice in a community." (Denning, 2010) ;
- Agility – "The ability of leaders and organizations to rapidly pivot to new problems and adapt to new circumstances." (Koutstaal, 2012) ;
- Learning organizations – "Exhibit systems thinking, personal mastery, mental models, shared vision, and team learning." (Senge, 2000)

Findings and Conclusions

A Strategic Thinking COI was initiated by the Director of Strategy and Innovation in the office of the Deputy Assistant Secretary of the Navy for Research, Development, Technology & Evaluation (DASN RDTE) to improve the NRDE's organizational agility and ability to innovate.

We acted as thought partners with the COI by joining with approximately 25 members of NRDE organizations in weekly teleconferences focused on innovation trends. Attendance was voluntary – not required by parent organizations. In a year of teleconferences the participants reviewed and reflected on hundreds of documents to learn about the technological and political environments that will drive the Navy's future investments and operations. Participants actively engaged in discussions and presented insights from conferences, related training exercises and technology demonstrations.

In support of the director's efforts, we developed a site on DoD's collaboration portal, All Partners Access Network (APAN), to support distribution of information within the COI. The site serves as an information repository for reports, conversation synopses and commentary, and enables collaboration across the R&D Plan's key strategic investment areas:

- Autonomous Systems
- Computing & Sensing
- Materials & Manufacturing
- Electromagnetic Maneuver Warfare & Cyber
- Weapons & Systems
- Energy

To expand the COI, we initiated efforts to identify potential research partners. We analyzed Naval Postgraduate School (NPS) Naval Research Program (NRP) data for topic sponsor connections between the NRDE organizations. We coached the topic sponsor on engagement methods to develop a COI that could promote learning, disseminate relevant knowledge, and seed a broader culture change. An opportunity for COI members to work together arose as they reviewed, discussed, and provided inputs to biennial revision of the Thirty Year R&D Plan. The rapid turn-around was one indicator that trust was increasing among members of the COI. Another was the increase in the number of people who participated in telecon discussions.

Throughout the year we advised the topic sponsor on shaping culture changes on many levels including: the alignment of strategy, organizational structures, rewards, people, and processes to support the desired end state.

Recommendations for Further Research

Continue to:

- Catalyze the Strategic Thinking Community of Interest
- Develop enterprise leadership and workforce strategies promoting team engagement, agility.
- Examine how the DoN might apply emerging knowledge of complex adaptive and anticipatory systems to inform organizational transformation.
- Prototype the addition of key identifiers to NPS research efforts to identify cross organizational research collaboration to enhance documentation and metadata strategies
- Ongoing review of collaboration tools beyond current portal, online at https://community.apan.org/wg/strategic-thinking/don_rdte_strategic_cell
- Explore metadata strategies for connecting NPS published products and data to diverse interests, suitable for futures planning and broad scalability.
- Use NPS student researchers as a bridge between NRDE labs and the fleet

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NPS-18-N304-A: A Systems Design Approach to Define the Requirements and Concept of Operations for Offensive and Defensive Seabed Warfare

Researcher(s): Dr. Paul Beery, and Dr. Eugene P. Paulo
Student Participation: Christopher Carr, Jahdiel Franco CIV, Cheryl Mierzwa, Lewis Shattuck, and Melissa Suursoo

Project Summary

This research defines and analyzes a concept of operations for seabed warfare. The research develops a broad definition of seabed warfare as a distinct warfare area via development of a systems architecture. Particular focus is given to the sensing, charging, and weapon characteristics relevant to seabed warfare. The research presents an initial set of system requirements for the employment of a "kill box" concept for seabed warfare as well as a definition of system functional and relevant physical components. The research develops an operational simulation in Matlab, directly linked to both the functional and physical system architecture products, that analyzes the performance parameters that have the largest impact on operational effectiveness. In particular, the research examines the operational impact of candidate unmanned undersea vehicles as enablers to the seabed warfare concept. That analysis is fed back into the system architecture to develop recommended system configurations and inform initial system requirements.

Keywords: *seabed warfare, undersea infrastructure defense, model-based systems engineering, simulation analysis, systems architecture*

Background

The Autonomous Undersea Vehicle Requirement for 2025 (Chief Of Naval Operations, 2016), defines missions that are current and projected for 2025. These missions include: intelligence, surveillance, and reconnaissance (ISR); anti-submarine warfare (ASW); anti-surface warfare (ASuW); strike, mine warfare, and naval special warfare. Beyond these historically defined mission areas, new areas are becoming increasingly important to the operational environment of 2025 and beyond, including counter-unmanned underwater vehicle (UUV) warfare, electromagnetic maneuver warfare, non-lethal sea control, and seabed warfare. This project focuses specifically on definition of a concept of operations for seabed warfare, which generally refers to the establishment and utilization of seabed infrastructure to disable, confuse, deceive, or destroy future military targets (Chief Of Naval Operations, 2016).

Broadly, seabed warfare utilizes seabed systems (or any system that interacts with the seabed) to perform traditional naval missions such as mine countermeasures, ASW, ASuW, ISR, and strike. The systems associated with seabed warfare must then be adaptable and configurable for different missions, environments, and tactical situations (Everhart, 2017). The concept has been detailed in (General Dynamics Mission Systems, 2017), which describes the utilization of seabed sensors to monitor and perform surveillance or upload/change UUV mission plans. From another perspective, the Underwater Great Wall, developed by the People's Liberation Army Navy (PLA(N)), constitutes a network of stationary sensors on the seabed that perform both surveillance and UUV/USV detection that is intended to act as a force multiplier for PLA(N) assets in a similar manner to the seabed warfare concepts explored in this research (Lin & Singer, 2016).

Findings and Conclusions

The purpose of this research was to inform development of an operational concept for seabed warfare. That effort was comprised of several stages: definition of an initial set of system requirements, development of Department of Defense Architecture Framework (DoDAF) compliant functional and physical architecture representations of candidate seabed warfare systems, and analysis of the performance of those systems using an operational simulation model. The effort dedicated particular focus to the operational utility of the Extra Large Unmanned Underwater Vehicle (XLUUV) as an enabler of seabed warfare.

Given that there is no standardized definition of seabed warfare, the research broadly defined seabed warfare as operations that involve undersea networks and systems capable of operating on the seabed, interacting with seabed systems, and taking actions against other systems. A significant contribution of the research was the integration of this generic definition with the definition from (United States Army, 2005) of a "kill box." The kill box was defined as "a three-dimensional fire support coordinating measure (FSCM) used to facilitate the expeditious air-to-surface lethal attack of targets, which may be augmented by or integrated with surface-to-surface indirect fires" with the goal of "(reducing) the coordination required to fulfill support requirements with maximum flexibility, while preventing fratricide" (United States Army, 2005). As noted, the tactic is typically applied to land-based operations, with additional specification of "blue kill boxes" for engagements conducted solely by air assets and "purple kill boxes" for shared air and land engagements. This research defined and proposed two new kill boxes, a "yellow kill box" that permits seabed engagement in the undersea and surface environments without further required coordination with the establishing headquarters and an "orange kill box" which permits near autonomous seabed engagement in the undersea and surface environments while also allowing surface to undersea indirect fires.

The kill box concept was used to define four missions essential to the deployment and execution of seabed warfare activities. The research identified and characterized three missions relevant to kill box deployment: intelligence preparation of the operational environment (IPOE), ISR and effects field delivery. One mission was identified and characterized to support kill box employment:

Engagement and Strike. DoDAF compliant architectural representations of these missions were developed, including a comprehensive OV-5a (operational activity decomposition tree) as well as associated lower level sequence diagrams compliant with the DoDAF OV-6c (event trace description). Subsequently a CV-6 (capability to operational activities mapping) was developed to formally link the operational activities detailed in the operational models to higher level capabilities associated with traditional warfare areas (such as ASW, ASuW, Strike, and mine warfare (MIW)).

The sequence diagrams generated as part of the architectural representations were used to define the activities and informational requirements for an operational simulation. Given the sequential nature of the majority of the activities associated with IPOE, ISR, Effects Field Delivery, and Engagement/Strike a discrete event model was built in Matlab to conduct detailed operational analysis. The simulation model was developed to support a trade-off analysis that compared the effectiveness of candidate systems as enablers of each seabed warfare mission as well as the performance parameters and design characteristics of those individual systems. The systems of interest were: an Extra Large Unmanned Underwater Vehicle (XLUUV) with a diameter between 84" and 120", a Large Diameter Unmanned Underwater Vehicle (LDUUV) with a diameter between 21" and 84", a Medium Diameter Unmanned Underwater Vehicle (MDUUV) with a diameter between 10" and 21", and a Small Unmanned Underwater Vehicle (SUUV) with a diameter between 3" and 10". All platforms were assumed to have inter-platform underwater communication using acoustic communication channels and were assumed to be required to operate in a GPS denied environment (both surface and subsurface) to isolate the performance of the individual systems. The number of systems available for each mission, the performance characteristics (such as probability of subsystem deployment and speed) as well as environmental characteristics (such as the size of the kill box) were varied for each simulation, and performance data was collected for each mission type.

Analysis resulted in the development of insights for each mission type. For each mission, it was evident that the size of the kill box was the primary driver of mission success. For IPOE, kill boxes larger than 500 nm^2 resulted in near zero probabilities of successful IPOEs for all systems. In order to gain insight into the relative performance of the candidate systems, additional experimentation was done where the performance of a single XLUUV was compared to the performance of approximately 10 LDUUVs, 15 MDUUVs, and 20 SUUVs (while this does not provide a direct comparison of system performance, it should provide insight into relative performance between systems of systems given the likelihood that larger number of small systems may be employed than larger systems). For kill boxes smaller than 500 nm^2 the XLUUV achieves mission success in approximately 41% of scenarios, the LDUUV configurations are successful in approximately 4% of scenarios, the MDUUV configurations are successful in approximately 67% of scenarios, and the SUUV configurations are successful in approximately 16% of scenarios. A similar analysis was conducted for the ISR mission; once again overall performance is near zero for kill box sizes exceeding 500 nm^2, with a strong indication that the kill box size should not exceed 250 nm^2. The SUUV is incapable of carrying the requisite payload to conduct ISR and accordingly was excluded from the analysis. As with IPOE, the MDUUV configurations provided the best performance for the ISR missions. For effects field delivery both the SUUV and MDUUV were excluded due to insufficient payload capability, and both the LDUUV and XLUUV demonstrated poor performance (and near zero performance at all kill boxes exceeding 250 nm^2). Finally, each system was analyzed in terms of its ability to support engagement and strike. The XLUUV was found to have the best performance, followed by the LDUUV, MDUUV, and SUUV. However, this preference is likely a result of the modeling convention; when larger numbers of small systems were employed there was an increased probability of detection by enemy systems (which prompted mission failures).

The data from the individual mission type analysis was aggregated to develop the following insights and conclusions. First, for IPOE missions the MDUUV is the preferred system for smaller kill boxes;

however, the utility of the MDUUV drops off sharply for the IPOE mission at kill boxes exceeding 500 nm^2, at which point the XLUUV becomes the preferred solution. For ISR missions the MDUUV is once again the preferred solution for smaller kill boxes, however there is once again a stark reduction in operational effectiveness for kill box sizes exceeding 100 nm^2. For both mission types field delivery and engagement/strike the XLUUV is the preferred solution, while the size of the kill box dominated the analysis and suggested the operational effectiveness was near zero for any kill box exceeding 250 nm^2. Broadly, the results indicated that the candidate systems can provide some utility in support of seabed warfare operations, but the size of kill boxes should be restricted to between 0-200 nm^2 for the systems examined in this research. More detailed results, as well as full descriptions of the kill box concept and the associated systems architecture and simulation model, can be found in (Carr, Franco, Mierzwa, Shattuck IV, & Suursoo, 2018)

Recommendations for Further Research

Future work for this project can be grouped into two categories: reduction of the number of assumptions made regarding the development of UUV technology and enhancement of the existing simulation to consider a more detailed operational environment. In the first area, future UUV technology has the potential to greatly improve operational capability, thereby allowing for the investigation of a substantially different behaviors in each scenario. For example, if UUVs have an organic evasion or avoidance capability the probability of mission success could be substantially increased. Similarly, the current simulation assumes that for ISR missions sensing devices were primarily sea mounted. If the U.S. Navy could retrofit an ISR device into a payload of an SUUV, it could be deployed by a surface ship or even potentially an XLUUV to improve performance of the ISR mission. Another obvious area for improvement is the introduction of increased capabilities for the XLUUV. As an example, if the XLUUV could be equipped with the same side-scan sonar payload capability as the MDUUV to conduct IPOE, then it could attempt to perform the IPOE mission and serve as a full mission solution for all missions. Finally, if UUVs were allowed to release an effects device, this would render the third mission obsolete and allow for execution of the kill box without risk to a high value asset. The XLUUV with split payload of a side scanner with full IPOE capability, ISR devices, and effects devices would constitute a potentially impactful system of systems for both deployment and execution of the kill box.

Regarding improvements to the simulation model developed in this research, there are multiple functionalities that do not currently exist that, if developed, could provide additional insight into the performance of candidate seabed warfare systems. The most important is likely an increased level of detail regarding the representation of the operational environment. Specifically, a model that can create both dynamic environments that change per mission with each scenario and static environments that are held constant within each scenario would result in the development of a more robust set of insights and conclusions. Features that would likely need to be implemented include seabed composition, salinity, depth, and temperature. An additional feature that should be implemented in subsequent analyses is varying field resolutions for both the ISR and effects devices. This would support investigation of system performance when the kill box has reduced capabilities due to deployment failures. Finally, the model did not consider an integrated logistics support (ILS) plan for maintaining and deploying the UUVs. Accordingly, potentially impactful variables such as battery recharging and maintenance downtime were not modeled in meaningful detail. Because some UUVs require full recharges between missions while others have field-replaceable batteries, this has the potentially to have a substantial impact at the overall strategy for the deployment of the kill box.

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NPS-18-N341-B: Automatic Generation of System Plans for Autonomous Unmanned Systems

Researcher(s): Dr. Valdis Berzins
Student Participation: No students participated in this research project.

Project Summary

The objective of the study is to leverage automatic programming in support of Systems Center Pacific (SSC-P) strategies for developing unmanned systems autonomy software. To apply artificial intelligence (AI) planning algorithms to this problem, research on suitable representations for mission plans and system plans is needed, along with principles for automatically deriving system plans from mission plans.

The study also seeks to improve man-machine teaming for controlling unmanned/autonomous systems that perform Navy missions. Mission plans should be described at a conceptual level natural for the human operators of autonomous systems and suitable for enabling one operator to control a team of multiple autonomous systems. System plans must be sufficiently clear and detailed to be carried out by fully automated systems. Specific research objectives are to investigate the following questions:

- What kinds of mission models are needed to support mission planning for teams of autonomous systems?
- How can we formulate the distributed adaptive planning general case to allow rigorous research in the area?
- How can autonomous systems plans be represented to enable automatic system plan generation from mission plans?

Keywords: *unmanned systems, autonomy, unmanned strategy, model driven development, automatic programming, planning*

Background

Prior software engineering research gave us breakthroughs in technology that improved the development of computer software and benefited real-time embedded systems. The automatic programming approach pioneered by the Naval Postgraduate School (Luqi & Berzins, Rapid Prototyping of Real-Time Systems, 1988, Luqi, Berzins, & Yeh, A Prototyping Language for Real Time Software, 1988, Luqi & Berzins, Execution of a High Level Real-Time Language, 1988, and Luqi & Berzins, Semantics of a Real-Time Language, 1988) utilized formal representations of system requirements, and in particular timing relationships among operations. Teams of autonomous systems, such as the Unites States Navy (USN) is envisioning deploying in the future, share many of the characteristics that made these formal mathematical methods, scheduling, and code generation so useful. Additional factors include uncertainty and a larger set of possible actions and states.

Mathematical formulations of the problem with a rigorous approach must be used. There are set theoretic, statistical and information theoretic aspects to be integrated for the application.

Previous work on handling uncertainty in plan generation for autonomous systems has focused on learning control in unknown environments and dealing with sensor uncertainty (Busoniu & Tamas, 2015). Most successful previous work on automatic program generation has focused on translation from goal models expressed using domain-specific higher-level languages, such as, "A Prototyping Language for Real Time Software" by Luqi, Berzins, & Yeh, "Execution of a High Level Real-Time Language" by Luqi & Berzins, "The Realizable Benefits of a Language Prototyping Language" by Herndon & Berzins, and "Generative Programming: Methods, Tools, and Applications" by Czarnecki & Eisenecker. Other previous work includes "Partial Evaluation and Automatic Program Generation" by Jones, Gomard, & Sestoft, "A New Architecture for Transformation-Based Generators" by Biggerstaff, and "Design Wizards and Visual Programming Environments for GenVoca Generators" by Batory, Gang, Robertson, & Tao.

Findings and Conclusions

This project is ongoing. We analyzed the references cited in this proposal as well as additional sources of information on control of multiple unmanned vehicles (UxVs), automatic software generation, and representation of stochastic scenarios, both published and from consultations with appropriate subject matter experts.

We also identified and analyzed relevant previous work on control of multiple UxVs, UxV mission modeling and planning, automatic software generation, and representation of stochastic scenarios. Then we consulted subject matter experts on background material and obtained feedback on the appropriateness of proposed frameworks and characterization of uncertain factors that will affect plans, identified relevant sets of mission states and possible UxV actions, and defined/modeled concepts related to vehicle control. We formulated initial mission and plan models, obtained feedback, and used an iterative refinement process to achieve adequacy. Thesis students will carry out case studies for validating adequacy of proposed representations of mission plans and vehicle plans representations for usability in realistic situations.

We interacted with subject matter experts from Lockheed Martin on representation of mission plans for the anti-submarine warfare continuous trail unmanned vessel (ACTUV) Sea Hunter. Associated analyses and background studies produced these conference publications (Berzins, Putting Teeth into Open Architectures: Infrastructure for Reducing the Need for Retesting, 2018, Berzins, Automated Methods for Cyber Test and Evaluation, 2018, and Berzins & Hernandez, Risk-Based Testing for Drones, 2018).

Recommendations for Further Research

If done properly, man-machine teaming can result in better performance than either isolated world-class human experts or isolated world-class software. Success in this direction depends on automated support for mapping high-level mission plans formulated in terms that are natural for human commanders into more detailed system-level plans that can be carried out autonomously by UxVs. Future research is recommended to explore particular UxV mission areas in greater depth, determine alternatives for how UxV commanders could interact with the swarms they direct, develop plan generation schemata and associated plan generation software, and then conduct exercises to determine which models work better in which situations.

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NPS-18-N343-A: Quantifying HEL Weapon System Performance through a Layer of Fog or Low Level Clouds

Researcher(s): Dr. Qing Wang, Mr. Ryan Yamaguchi, Dr. Haflidi Jonsson, and Ms. Hway-Jen Chen
Student Participation: Capt Zachary Daniel USAF and Maj Benjamin Wauer USAF

Project Summary
This project addresses critical issues regarding the effects of low-level cloud/fog on the operational performance of high energy laser (HEL) weapons. This topic represents a large knowledge gap in operating the HEL weapons that inevitably goes through the atmosphere that is often filled with water hygrometers. This research included three parts: instrument development, field measurements, and data analyses. A fog microphysics sensor was modified to fit the application of measuring from a stationary platform and was integrated into a trailer-based laboratory for aerosol and fog sampling. For data collection, we made continuous measurements in two locations in the Monterey Bay area, one at a farm field at the coastline and one further inland over mostly concrete surface. These measurements include both meteorological data as well as propagation data. Data analyses focused on the observed scintillation and attenuation. The amount of optical energy attenuation through the fog layer and the role of scintillation in foggy conditions are being analyzed as part of the thesis work of Captain Zachary Daniels who will graduate in March 2019.

Keywords: *fog, high energy laser (HEL) weapons, atmospheric effects, boundary layer turbulence*

Background
The U.S. military forces have demonstrated the capability of a 10-kW high-energy laser to track and engage a variety of targets under adverse, laser-unfriendly weather conditions over the maritime environment, such as fog, rain, and high wind. However, there has been little effort devoted to develop a quantitative understanding of fog/cloud parameters affecting present day laser system beam propagation at these power levels. Understanding these effects become critical for predicting effectiveness in engaging advisories with a given confidence and range under fog/cloud conditions.

Findings and Conclusions
Predicting atmospheric effects on laser systems has attracted much interest in recent years with increasing prominence in missile defense, tactical, and communication applications. Laser systems permit graduated engagements that could range from a simple disruption of adversary activities to their destruction. The atmosphere, particularly the lowest few kilometers, has profound effects on HEL system performance. Laser weapons will encounter substantial scattering in conditions such as fog and clouds. These effects need to be characterized in terms of descriptive quantities for fog and clouds from a meteorological forecast model outputs or routine ship- or surface-based measurements. In addition, although the absorption extinction coefficient of hydrometeors for the visible wavelength is generally small, the massive incident energy from a HEL beam potentially leads to substantial absorption and results in modifications to cloud/fog layer properties and hence the HEL propagation. This indirect effect of the fog/cloud layer on HEL propagation should be investigated as well. Lastly, strong turbulence is present in fog/clouds with large temperature perturbations. The impacts of the fog/cloud optical turbulence have not been investigated.

This research intends to address the above issues using an observational approach. In visible and infrared (IR) wavelengths, light propagation through the atmosphere is affected by two phenomena: absorption and scattering by air molecules and absorption and scattering by solid or liquid suspended particles present in the atmosphere. These particles include aerosols as well as fog. A critical part of our observational work was to develop adequate sensors to quantify the fog characteristics. To that end, we modified a cloud droplet spectrometer designed for small aircraft for deployment on a stationary platform such as a trailer. This modification included enclosing the sensor in a pipe and attaching a small fan to draw air through the sensing volume. The flow rate was measured in order to quantify the number concentration of the fog droplets. This sensor was integrated into a trailer laboratory to make continuous measurements of fog microphysics, aerosol scattering and aerosol absorption. The instrumented trailer, together with a tripod mast with high-rate turbulence measurements, and optical scintillation and attenuation sampling were made at two sites, one at a farm land near the coastline (13-15 July 2018), one at the Marina airport a few kilometers from shore (15 – 21 July 2018). Both sites were selected because of the frequent occurrences of fog. In addition to the above-mentioned sensor suites, we also augmented the measurements with multiple rawinsonde (weather balloons), laser ceilometer (cloud base height and aerosol backscatter), and tethered balloon with an optical turbulence sensing package. Furthermore, the suite of sensors was shipped to Canada to collect more data leveraging with another field work on fog physics.

Fog events were encountered on multiple days during the intensive measurement period. Collectively, we collected a large amount atmospheric environment and optical propagation data, simultaneously. Our measurements showed clear correlation between the received signal and the presence of fog. We also observed strong location variability of the optical structure parameters indicating the atmospheric scintillation effects. Data analyses is still ongoing as part of Captain Zachary Daniels' master's thesis work. Captain Daniels is to graduate in March 2019. In addition, Major Benjamin Wauer intends to use the dataset in his Ph. D dissertation work.

The data we collected during this project is unique in many ways. This is the first complete dataset that has both measurements of the optical propagation and its propagating environment. This is a critical dataset for us to gain some preliminary knowledge of the fog effects on HEL weapons. As part of this project, we have established close collaborations with Naval Air Warfare Center Weapons Division (NAWCWD), China Lake on optical propagation measurements. We also worked with scientists at the Naval Postgraduate School's (NPS) Center for Interdisciplinary Remote Piloted Aircraft Study (CIRPAS) on fog/aerosol measurements and processing. The field work was made possible because of the help of many Navy reservists as volunteers.

Recommendations for Further Research

Measurements of turbulence using a sonic anemometer can be problematic although previous published research suggested good results. Recommendation #1 is to explore an alternative way in measuring wind turbulence in fog or light rain conditions. Recommendation #2 would be the need for more observations to generalize findings from this research.

NPS-18-N344-A: Fostering Innovation in the Naval Research & Development Establishment

Researcher(s): CDR Sue Higgins USN Ret., and Dr. Erik Jansen
Student Participation: No students participated in this research project.

Project Summary

An organizational design framework serves to better understand how cultures of innovation develop among organizations comprising the Naval Research & Development Enterprise (NRDE). Based on conversations and interactions with NRDE members and stakeholders, we sought insights about designing for innovation. These fell into three design domains. First, in the Strategy domain, individuals are working to make sense of the theme and vision of agility. We found individuals engaged in understanding agility, and others remaining skeptical. We found considerable appreciation for a vision – by whatever name - associated with flexibility, speed, learning, collaboration, and opposed to bureaucracy and business as usual. Second, in the Structural domain, non-bureaucratic options are being adopted and diffused in acquisition and contracting and in design processes. There are exemplars of more organic, decentralized structures with greater lateral communications and information sharing. Third, in the Human Resources domain, the importance of talent management and reward systems (e.g., taking calculated risks) seems appreciated, but progress in this domain may be lagging. We find some frustration for resistance to change as well as some top-down design changes that might have been improved by alternative design processes. More progress can likely be made in systematically investigating how to develop the various skills associated with leadership and entrepreneurship and in integrating these into syllabi and curricula for training and education.

Keywords: *innovation, agility, collaboration, organizational design, culture*

Background

The NRDE faces a dramatically changing context and environment. Its environment is increasingly uncertain, unstable and complex, providing new threats and opportunities. The role of commercial enterprises has increased. Disruptive technologies will likely revolutionize all levels and functions of warfare and command and control. Peer competitors are emerging, and non-peer competitors present new asymmetric threats. Resources are unlikely to increase to match the challenges. Innovation strategies thus require efficiency, effectiveness, flexibility, speed, and capabilities to collaborate, which some might characterize in terms of a higher-level construct of agility.

An organizational design framework may provide leverage for developing cultures of innovation, in terms of management and leadership practices and for training and higher education.

Organizational design begins by identifying critical strategic design values and capabilities (e.g., agility, collaborative capacity, speed). Policies to enable these capabilities are developed for design domains, including Structure (e.g., decentralization, organic processes), Work and Information Processes, and Human Resource Practices (e.g., talent management, reward systems). This creates the context that shapes culture.

Findings and Conclusions

This qualitative research was designed to generate insights related to mid-range theories involving innovation in NRDE's inter-organizational context. We engaged NRDE members and stakeholders to better understand the policies and practices associated with agility and innovation within and across NRDE's organizations.

This included conversations and observations of interactions among NRDE members and others in the related, larger naval research community as they worked to advance innovations. It included reflections of NRDE members about previous successes and expectations and concerns for future policies and practices. The research was exploratory, did not use random or representative sampling, and focused on organizational level and inter-organizational level variables.

As individuals reflected on their work of creating innovations for warfighters, they noted policies and practices that enhanced or inhibited their efforts. Conversations most often supported well-known insights in the research literature. One senior informant said, "We don't do a good job of educating our leaders about organizational design." Informants were savvy, intelligent, experienced, and committed to their missions; they were impressive in what they had learned in "the school of hard knocks" and often seemed hungry for "thinking tools" that could explain and organize their knowledge. Some raised critical design issues that reinforced the design process values of avoiding top-down, hierarchical approaches and including diverse participants who are pushed and encouraged to challenge the status quo. Thus, a key finding was the need to use a process for designing NRDE organizations that is congruent with the innovative processes sometimes pushed to solve operational problems and develop new products.

Recommendations for Further Research

We encountered individuals working to introduce design approaches akin to what is branded as Design Thinking. This was impressive to the researchers, but we are concerned that – even when or if successful – there is not a systematic approach to learning what is working or not working and why it is working or not working. This risks making a possibly valuable set of processes and procedures into an apparent fad. The military has the capacity to systematically learn from its design efforts, and to use that learning in its training and educational curricula. Much of our research suggested existing concepts, models, and theories that can serve to understand designing for innovation and collaboration and provide a framework for research, training, and education.

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NPS-18-N354-A: Benchmarking Human Resources Services Innovations and Best Practices with Industry

Researcher(s): Dr. Kathryn Aten, Ms. Anita Salem, Dr. Marco DiRenzo, and Ms. Sally Baho
Student Participation: Helene Carniac, and Mr. Tyller Williamson CIV

Project Summary
Human resources (HR) practices have been evolving to accommodate changes in the business and social environments. Recent research by the authors indicate that in the U.S. Navy institutional norms and work practices are evolving and are likely to have increasing impact on recruiting and retention.[1] The current research will investigate changes in industry HR on-boarding practices for executives through a systematic, narrative literature review and interviews of subject matter experts. This research will support innovation in Department of Navy (DoN) HR practices by providing the DoN HR community with (1) knowledge of innovative industry practices and (2) recommendations based on an assessment of the applicability of industry best practices to the Navy's specific context.

Keywords: *onboarding, executive onboarding, leadership development, leader assimilation, leader's role transitions, federal, SES.*

Background
HR practices are continually changing to accommodate changes in the business and social environments. This research will investigate and assess exemplary HR on-boarding practices for those in a leadership role through a systematic, narrative literature review and interviews of subject matter experts. This research will support innovation in DoN HR practices by providing the DoN HR community with (1) knowledge of innovative industry practices and (2) recommendations for improving civilian onboarding practices for Navy executives.

Findings and Conclusions
Executive onboarding, as defined by the Office of Personnel Management (OPM), is "the acquiring, accommodating, assimilating and accelerating of new leaders into the organizational culture and business.[2] This paper looks at recommended practices for executive onboarding by first examining the role of leadership in an organization and then by looking at recommended practices for onboarding new leaders. Combining a literature review of industry and academic publications with in-person interviews, the researchers explored four research questions:

- What are current practices in executive on-boarding?
- What are the desired outcomes from an on-boarding process?
- How do you track those outcomes?
- What are some of the barriers and opportunities in developing leaders?

To date, researchers have completed the literature review and conducted interviews with over 50 industry professionals from companies such as Plantronics, Intel, Xilinx, Disney, Adobe, and the Gates Foundation. A student thesis is in progress and interview data is being analyzed. Preliminary findings indicate that one must first understand the roles and goals of effective leadership in order to assess the best practices in executive onboarding. Richard Bolden, and others from the Centre for Leadership Studies, have identified a number of measurable effects associated with successful leadership.[3] These effects include effects related to personal development, strategy, culture, and relationship building.

Personal development involves what the Navy calls 'Leading Self' and 'Leading Programs'.[4] It includes developing individual leadership skills such as communication, ethics, problem-solving, conflict management, and resilience. It also includes developing competence, setting career goals, establishing continual learning processes and understanding personal work preferences and attitudes. Measurable effects include personal productivity, skill competence, self-awareness, ability to think strategically, and turnover.

Strategic outcomes are those that support specific organizational goals. Strategic effects include profitability, reduced wastage, the health of partnerships, and innovation. Strategic activities include determining risks and problem areas, articulating and building consensus on the vision, considering improvements in organizational structure, identifying early wins, and aligning with senior leadership. For the Navy, the skills associated with strategic outcomes are called "Leading Program" and "Leading Institutions."[5]

Cultural integration is especially important when considering the role culture plays in building a highly functioning organization. In a 2015 survey by McKinsey, executives said in retrospect, they would have acted much quicker in putting their teams in place and in understanding the organizational culture.[6] Cultural integration activities include everything from understanding normal protocols to building an environment of safe question asking and ethical behavior. Measures of effectiveness for cultural integration include shared values and lower resistance to change, increased productivity, decreased absenteeism, and a willingness to work overtime. In the Navy, cultural integration is tied to 'Leading Teams' but is not specifically called out. [7]

Relationship building is the final leadership skill and is one that is often thought to be the most important in becoming an effective leadership and delivering strong organizational performance. Relational effects include increased accountability, high levels of employee engagement, efficient team work, and ongoing feedback and situational awareness. Relationship building activities include communicating with key stakeholders, peers and superiors, meeting with direct reports and staff, developing others, and joining in networking activities. For the Navy, this is described as 'Leading People' and 'Leading Teams'. [8]
These are the metrics across which any executive onboarding program should be evaluated.

Recommendations for Further Research

Because leadership is a process of influencing people, it can exist at any level and requires a long term developmental approach to talent management that begins with recruiting and continues throughout a career. The final report will identify common leadership gaps, problems with existing onboarding programs in industry, and best practices for implementing an onboarding program.

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NPS-18-N363-A: DoD Agile Software Development Early Phase Cost Modeling

Researcher(s): Dr. Raymond Madachy
Student Participation: No students participated in this research project.

Project Summary

Software effort estimates are necessary and critical at an early phase for decision makers to establish initial budgets, and in a government context to select the most competitive bidder for a contract. The challenge is that estimated software requirements is the only size information available at this stage, compounded with the newly increasing adoption of agile processes in the United States (U.S.) Department of Defense (DoD).

The objectives are to improve cost estimation by investigating available sizing measures, and providing practical effort estimation models for agile software development projects during the contract bidding phase or earlier.

This analysis explores the effects of independent variables for product size, peak staff, and domain on effort. The empirical data for model calibration is from 20 industrial projects completed recently for the US DoD, among a larger dataset of recent projects using other lifecycle processes.

Statistical results showed that initial software requirements is a valid size metric for estimating agile software development effort. Prediction accuracy improves when peak staff and domain are added as inputs to the cost models.

It is concluded that these models may be used for estimates of agile projects, and evaluating software development contract cost proposals with inputs available during the bidding phase or earlier.

Keywords: *agile software processes, software cost estimation, software effort, software size, software requirements, requirements volatility, peak staff, domain, productivity, interfaces*

Background

In the U.S. DoD, it is necessary and most critical to estimate software development cost in early lifecycle phases when limited data is available. These initial estimates are used to evaluate proposals for government source selection, and to establish initial program budgets. More realistic estimates in the beginning will minimize project cost overruns.

The problem is compounded because agile software processes are increasingly used in the DoD, and acquisition practices must keep pace with the changes. Agile development processes (e.g. Scrum, Extreme Programming) have been more prevalent in industry, and are now being adopted more across the DoD and other government agencies. Thus, there is a dire need for new, accurate, credible cost models calibrated to actual project data. This study uses empirical data from completed industry projects extracted from a DoD database. The majority of agile projects were submitted in the last two years.

The results are significant because the data provides initial empirical-based insight into DoD agile projects. It also introduces the first cost model calibration to completed agile software projects in the database, and a first comparison of productivity with traditional processes.

The subset of agile projects is the primary focus of this work. Results of the larger study covering all projects and process types are not addressed in this paper, except for a summary comparison of productivity for agile vs. non-agile projects.

An important distinction of this approach is using early phase initial estimates for model inputs and historical calibration of the cost model. This is pragmatic since those initial estimated inputs are the only information available for the early phase budgeting.

The source of actual industrial data for the DoD is the Cost Assessment Data Enterprise (CADE) repository (http://cade.osd.mil) owned by the Office of the Secretary of Defense for Cost Assessment and Program Evaluation (OSD CAPE). The quantitative project data is contained in Software Resources Data Report (SRDR) records. The DoD acquisition process outlined in the DoD Instruction 5000.02 policy Operation of the Defense Acquisition System mandates the SRDR as a regulatory contract reporting requirement (Department of Defense, 2011).

The SRDR is used to obtain both the estimated and actual characteristics of new software developments or upgrades. Both the government program office and later the software contractor submit the SRDR. It constitutes a contract data deliverable for contractors that formalizes the reporting of software metric and resource data.

Previously, early phase cost estimation relationships for the DoD were developed from SRDR data in the CADE repository using size in source lines of code and military application domain as predictors (Clark & Madachy, 2015). However, none of the data was for agile projects.

In 2009, a new Defense Authorization Act required DoD to implement a new acquisition process for IT systems (Department of Defense, 2016). This new process included principles of agile development such as early and continual involvement of the user, multiple rapidly executed increments or releases of capability, early successive prototyping to support an evolutionary approach, and a modular open-systems approach.

The current SRDR forms include identification of the software development process used with agile being an option (see Section IV-B for more details). Supplemental details of the processes can be provided in an associated data dictionary. Agile process definitions for the DoD and implementation guidelines are provided in (Department of Defense, 2016) and (Government Accountability Office, 2012).

Findings and Conclusions

The regression analysis indicates initial software requirements is a valid size measure for predicting agile software development effort at early phase. An effort estimating model only based on software requirements is statistically significant but not very accurate. The model accuracy improves after peak staff and super domain are incrementally added to the model.

The models may be used for validating contract cost proposals for agile software projects for independent government cost estimates, as the input variables used in the study are often available during the bidding phase.

Since the data was collected at the component level, the resulting models may not be appropriate for projects reported at the aggregate level due to the excluded cost of subsystem integration. The models have also not been validated outside of the regression models' dataset size range.

A related result of interest from this first batch of CADE data containing agile projects is a productivity comparison. The dataset indicates that agile software projects appear to be more productive than non-agile projects, and this will be updated in the future with larger samples.

There are some possible threats to validity. This study only examined the impact of software requirements, peak staff, and super domain on development effort. A future investigation should analyze the impact of other cost drivers such as percent requirements reuse, volatility, process maturity, and personnel experience.

The study did not apply a size complexity weight factor to the initial software requirements to account for the fact that some requirements can be more complex than others. A future study will mitigate this shortcoming by asking each organization to apply discrete weights (easy, nominal, and difficult) to the estimated requirements similar to the one used in the Constructive Systems Engineering Model (Valerdi, 2005).

In principle, the analysis framework may apply to commercial sector systems, but this study did not have the data to test this hypothesis.

A larger dataset beyond 20 projects is preferable to increase model validity and accuracy, and this data collection is ongoing.

Recommendations for Further Research

There are important areas of future work to improve the usefulness of these model types for practitioners. The software granularity of modeling can be finer. We intend to develop similar regression models for agile projects using a dataset greater than 20. We will also examine the impact of software requirements on software development effort while controlling for the effects of development process, process maturity, and percent reuse.

Given the process trends, DoD acquisition practices must keep pace with the changing processes. Our research will support this on technical and regulatory levels. Results will be transitioned at DoD venues.

New cost estimating relationships (CERs) for agile processes across the domains will go in the next edition of the Software Cost Estimation Metrics Manual for Defense Systems. Recommended improvements to the SRDR to cover agile processes and size measures will also be submitted to the OSD CAPE for incorporation.

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NPS-18-N393-A: Development of Shipboard Equipment Shock Survivability Assessment Technique

Researcher(s): Dr. Young Kwon and Mr. Jarema Didoszak
Student Participation: LT Brian Gottfried USN

Project Summary
Navy ships are expected to perform their mission in an arduous combat environment. Shock loading from non-contact explosions is one of many mechanisms that have the potential to cause extensive damage to these vessels. In particular, underwater explosions (UNDEX) resulting from mines, torpedoes, or other waterborne explosive devices pose considerable risk not only in structural failure, but also in terms of equipment damage, personnel casualties, and ultimately mission kill.

So critical is this issue that the Navy has outlined shock hardening requirements for surface combatants in OPNAVINST 9072.2A. Per this instruction, the Naval Sea Systems Command (NAVSEA) established general guidelines for the verification, validation, and certification of surface ship shock hardness in the technical publication T9072-AF-PRO-010. While this document establishes a general method of equipment qualification, standardized criterion that constitutes a survivable design is less rigidly defined.

This current effort focuses on assessment of the current technique so as to investigate uncertainties in the shock level response experienced during the shock verification process as compared to the actual failure parameters. Using basic analytic approaches and finite element modeling and simulation, an in-depth review of shock failure cases was conducted. Key parameters influencing the response and uncertainty in failure prediction were ascertained. These results will be used in follow-on work to generate a standardized procedure for the determination of shock related failure in shipboard equipment. It is anticipated that once validated, this approach can then be applied across various shipboard equipment and systems in the evaluation of shock hardening.

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

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

To accurately predict the shock response of the ship system, several key items must be agreed upon. First it is imperative that the goal of the verification be clearly stated. Ideally a predetermined set of failure criteria for each critical element within the ship system would be established as a means to assess the performance under extreme loading conditions. In order to do this, these criteria must be defined based on some meaningful measures such as peak acceleration, limiting pseudo velocity, maximum displacement, yield stress, etc. (Cole, 1948). However, this is an extremely daunting task with the depth and bread of systems, subsystems, and equipment contained within the ship, in addition to the ship structure itself and human occupants. Furthermore, during the design phase, which would be the most ideal time to perform the shock verification, many of the final system characteristics are yet unknown, or may change prior to delivery of the vessel. Moreover, the loading condition itself must be well defined based on the intended result. What may constitute failure in one system, and thus present as a useful indicator, may not adequately address the failure mechanism in another. In addition, there is the impact of transitory failures, cascading functional failures, and indeterminate failures that only reveal themselves in testing. The uncertainty in potential location, attachment, and orientation direction of the item onboard ship, all make for nearly an infinite test space for evaluation.

The cost and time necessary to devolve each critical element into a specific criterion, accounting for all the connections and interactions crossing the control volume, even in the simplest sense of a "pass or fail" test, is extremely prohibitive to a ship acquisition program. Hence when forced to use this rudimentary approach, the lack of detail in this type of testing provides great uncertainty in the measure of proximity to the true failure point. Thus in an operational sense, the engineer, and more importantly the operator, is truly unaware of how sensitive the item may be to shock related failure given a particular shock event.

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

Clearly the end goal is to find the best suited verification procedure in terms of cost, schedule, and performance. In order to do this, we first must ask "Are the acceptance criteria adequate?" And secondly "What can be done to reduce the uncertainty in the verification process?" However the item that needs to be called out in both the physical testing and the computer modeling and simulation is the *uncertainty quantification*, that is, the gap, between the measurable or deterministic performance result and the acceptable value. Currently this is somewhat ambiguous.

The MIL-DTL-901-E, which provides the basis for shock qualification testing, offers additional options to vendors in order to demonstrate that their equipment has been deemed worthy of acceptance for onboard ship use in a shock environment. Yet it lacks definitive criteria beyond simple categories of non-operational, visually damaged etc., which would lead to a "failure" rating. There is no quantitative rating of the performance for the equipment being tested in most cases, unless specifically called out as part of a contract.

For instance, for a surface ship deck mounted piece of equipment, the Light Weight Shock Test Machine (LWSM) test prescribes a series of hammer blows at various drop heights of different orientations for equipment of less than 550lbs. Inherent in this test is the assumption that the equipment being tested will experience a level of shock severity high enough to justify that if it still functions accordingly, with no visual damage after the test, then the equipment will always function properly once placed anywhere in the shipboard environment under realistic shock loading. This would lead one to surmise that the impact velocity, acceleration and displacement delivered by the loading mechanism in the LWSM test is sufficient to assess the equipment for all practical shock loading conditions that may be anticipated based on the shock level classification of the equipment. In fact this may not always be the case.

While the guidance provides the ability to physically test equipment either through mechanical testing such as by the use of shock test machines, it also allows for live fire testing using explosives. This too introduces variability in the determination of what actually is the prescribed shock loading, and the resulting acceptable shock response level. Mechanical and explosive testing deliver different system response due to the nature of their loading profiles. Though similar, the amplitude and frequency are different in each case when comparing several accepted verification tests excitation inputs.

In order to drive out this type of uncertainly, it is proposed that the verification process be linked more explicitly to a quantifiable engineering characteristic such as velocity or acceleration, etc. rather than operational, functional, or visual verification of degradation or damage. Since it is impractical to test such vast quantities of equipment configurations using realistic live fire testing, as is the case for high production rate products, nor could the government require detailed finite element models that had been validated separately. For extensive simulation in an infinite series of "cases", an adaptable methodology rooted in physics-based investigation must be pursued.

During the last several decades the U.S. Navy has collected tens of thousands of record data inputs and their corresponding response histories aboard ship during live fire explosive tests. Full ship shock and FSP testing has provided this extensive acceleration, velocity, and displacement database, though the majority of this data pertains to the characterization of only the input loading and base response rather than the actual response of the particular system or equipment. The unique response of individual equipment and its critical components is left for more specialized testing that is not generally prescribed by the MIL-DTL-901E. In general shock test acceptance criteria are based in the reporting of a) physical performance parameters, b) momentary malfunction, and c) permanent functional impairment, in cases where specific criteria is not called out by acquisition documents. However, this absence of detailed response measurement specification leads to an uncertainty in equipment performance.

Anecdotally, if a pump and motor setup, properly restrained with all of the required inputs and outputs, in normal operation, were tested on the FSP in accordance with the MIL-DTL-901E, the successful outcome of the testing would report that unit operated as expected after the shock event, with no momentary lapse of functionality and no apparent visual damage to the equipment. Yet what this fails to provide is any definitive value relating the proximity of the critical component within this equipment to its failure state. Additionally, it does not give designers insight into which failure mechanism the equipment is most susceptible to as a result of the testing.

Findings and Conclusions

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

An assumption is that the engineer will use a ship finite element method (FEM) structural model and hydrocode that has been validated and verified against live fire test and evaluation (LFT&E) test data from previously conducted FSST. This has potential to help reduce risk in ships under design rather than following the traditional path of full ship shock testing once the ship has been delivered. Likewise today's equipment models are of sufficient fidelity to conduct detailed analysis and will have been vetted using modal analysis, testing, or other means as provided by vendors.

Measured response data from current test methods (LWSM, medium weight shock machine (MWSM), FSP, Deck Simulating Shock Machine (DSSM), etc.) has been used to trend responses using quantifiable measures such as acceleration, velocity, and displacement. This information along with stress and strain data will be used to codify shock acceptance criteria in the follow-on study. Using the given shock loading levels outlined in the MIL-DTL-901E, FEM models, and predicted equipment response, failure envelopes would be created to provide measurable thresholds against which to compare the actual shock response. The end result would be to set conservative measurable limits to acceptable shock envelopes which if exceeded would cause equipment failure (physical damage, non-operational status resulting in mission degradation, or mission loss).

Recommendations for Further Research

Validation of this approach is currently in progress at the Naval Postgraduate School through the use of existing validated ship FEM models, generic equipment models with clearly defined functional failure, and simplified mass spring systems representing equipment. In addition, the pitfall of the current practice is also investigated. At the end of this research, a report will be generated to delineate a reliable guideline for certifying equipment as survivable under threat level UNDEX conditions.

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N1 - Manpower, Personnel, Training & Education

NPS-18-N046-A: Determining Effects of Training in Virtual Environments upon Implicit Learning

Researcher(s): Dr. Meghan Q. Kennedy, Mr. Perry McDowell, and Ms. Rabia Khan
Student Participation: CDR Chris Angelopoulos USN

Project Summary

The Department of Defense (DoD) is relying more heavily on virtual environment and augmented reality for training purposes. However, little is known as to whether the use of a virtual environment (VE) and augmented reality (AR) are as effective in training tasks that require fine motor skills. This research measured human precision and efficiency by comparing augmented reality cued (ARC) and traditionally cued (TC) maintenance procedures in five tasks designed to elicit absolute, cumulative, absolute referential, and complexity errors across both ARC and TC conditions. Results indicate ARC procedures are statistically more efficient for human precise placement tasks of small parts, while precision is roughly equal. The assembly task, analogous to an assembly procedure, is statistically both more efficient and more precise using ARC vice TC procedures. Results indicate that ARC procedures for small part placement and assembly tasks are more efficient, faster, and in most cases at least as precise as TC procedures.

Keywords: *virtual environments, augmented reality, training, human precision, human efficiency*

Background
Most Navy classrooms/labs rely heavily upon training technology in general, and virtual simulations/ environments in particular, to help deliver instruction and content to students. Research has demonstrated the effectiveness of both VE and AR for training certain skills. For example, use of visual or haptic cues to keyboard entry tasks in VE lead to greater motor learning than perceptual learning (Kim, Johnson, Gillespie, & Seidler, 2014; Waller, Hunt & Knapp, 1998). AR has been used successfully to evaluate mechanics' performance with a torque wrench and in training assembly tasks to novices (Aviation Voice, 2017; Tang, Owen, Biocca, & Mou, 2003). Novices who used AR training made significantly fewer errors and completed the assembly task in significantly less time than novices using either print instructions or computer aided instructions (Tang et al, 2003).

Findings and Conclusions
The primary research question was to ascertain the effects of replacing traditional training with training in VE and/or AR in terms of precision and efficiency. We hypothesized that participants who receive VE/AR training would make fewer errors and complete an assembly task more quickly than participants receiving traditional training. The assembly task consisted of making approximately 50 correct actions to assemble a large object out of erector set pieces, bolts, and wire. Error was operationalized as any of the following: by misconnecting parts, missing parts, incorrect positioning of parts, incorrect direction of parts (bolts or wires), or misrouting of wires. Thirty-four Marine maintenance personnel participated in the study. Microsoft HoloLens was used for the AR condition. A within person experimental design was used such that 18 participants first completed the assembly task with traditional training (traditional condition) and then completed the task with AR training (AR condition); the other 18 completed the tasks in the reverse order (i.e., AR then traditional). To assist with attaining precise measures of completion time and precision, a video camera recorded the participants' performance. This study was approved by both the Naval Postgraduate School (NPS) and United States Marine Corps (USMC) Institutional Review Boards (IRBs). CDR Angelopoulos designed and conducted the experiment, and analyzed the data.

Results supported the hypotheses. Paired *t*-test indicated that time to complete the assembly task was significantly shorter in the AR condition than the traditional condition (Mean difference: 87.21 sec, 95% CI: -166.15sec to -8.26sec, $t(30) = 2.26$, $p = .03$). Participants also made significantly fewer errors with the AR condition than traditional condition (mean difference = 25.53mm; 95% CI: .01mm to .029mm, $z = 5.64$, $p < .0001$).

Recommendations for Further Research
Results indicated ARC procedures for small part placement and assembly tasks, including wiring, are more efficient and precise than traditional procedures. Several lines of future research exist, including the following:

- This study examined a task that required the manipulation of small pieces and fine motor skills. Are similar results found when assembling something made of larger pieces? Is there a definable curve or correlation to size of parts and human precision and efficiency?
- Participants in this study were Marine maintenance professionals. Do these results generalize to other military populations?
- The assembly task was designed to meet the requirements of a controlled scientific experiment. Would results generalize to an actual assembly task currently trained by the DoD? Is there a definable transition where intuitiveness, simplicity, or repetitiveness of a task overrides the benefits of ARC?

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NPS-18-N068-A: Qualitative Measures of and Guidance for Navy Inclusiveness

Researcher(s): Dr. Steven B. Hall
Student Participation: No students participated in this research project.

Project Summary

This project undertook a deep dive investigation into the nature of the challenges involved in *nontrivially* transforming the existing Navy culture so as to become more 'inclusive'.

The envisioned Navy organizational transformation, towards greater 'inclusiveness', has been promoted as yielding a variety of beneficial organizational effects ranging over: the elimination of irrational and detrimental discriminatory behavior; improved personnel retention rates; enhanced organizational innovation capabilities; and elevated operational effectiveness and readiness. In short, enhanced organizational 'inclusiveness' has been cast as a panacea for all that can ail an organization.

While a popular perception persists of the post-World War II Department of Defense (DoD)/United States Navy (USN) as playing an exemplar role in integrating the growing cultural/identity diversity of the American people into an effective war-fighting capability, more recently a sense that more needs to be done has emerged.

But despite considerable recent efforts within the Navy/DoD (as well as the federal government and the commercial sectors) to *institute* more inclusive organizations, this study found that the notions themselves, regarding what constitutes an 'inclusive' organization/culture, are effectively operationally undefined. This failure, to clearly articulate the intended meaning of these concepts, and consequently the inability to meaningfully measure them, has effectively thwarted all meaningful attempts at making pragmatic progress in this direction.

An analysis of the New Inclusion Quotient (NewIQ) factor of the Federal Employee Viewpoint Survey (FEVS) as well as the 'Inclusion at Work' component of the DoD Defense Equal Opportunity Management Institute (DEOMI) Organizational Climate Survey (DEOCS) found these surveys, in particular, to provide little meaningful indication of the inclusive status of surveyed organizations. Consequently this study undertook a systematic deconstruction of the dominant 'Diversity & Inclusion' community's notions of 'inclusiveness', and its anticipated dividends, to eventually reveal a suite of underlying and unexamined assumptions that, when more carefully examined, reveal a promise of dividends that are unlikely to be fulfilled without both a substantial recharacterization of what we mean by 'inclusiveness' *along with* a broad Navy culture transformation, more attuned to the rapid changes brought about by the information age.

A new, more 'inclusive' supportive, '21st Century Navy' culture is characterized in this 100+ page report that is founded less on the traditional values of 'heroic sacrifice' and more on the 'embrace of uncertainty and adaptability'.

A suite of cross-validating measures is recommended that rely less on the member's *subjective* and personal assessments of the organization's inclusiveness and more on objective measures directly tied to the presence of the organizational properties being sought.

Recommendations are provided for how such a cultural transformation might be ushered in via a combination of modified recruitment training and a leadership led/championed Continuous Improvement Process program.

Keywords: *Navy inclusion, diversity management, retention, innovation, organizational effectiveness, cultural transformation, equal opportunity, adaptability, resilience*

Background

The United States department of Defense (U.S. DoD) and the United States Navy (USN) have long been challenged by the task of integrating a culturally and social diverse workforce into a cohesive and effective fighting force.

In part this diversity integration challenge is being driven by larger federal government initiatives (U.S. Equal Employment Opportunity Commission, 2018) concerned with ensuring that equal opportunities are available to federal workers who possess social identities which are, or have been, subjected to systematic discrimination. And, in part, it is being driven by the fact that today's Navy recruits, independent of any external pressures to avoid discriminatory practices, simply come from increasingly diverse backgrounds.

While integrating a workforce of diverse cultural, ethnic, and social backgrounds into a highly effective, committed and disciplined fighting force can be a challenge, that very diversity has also promised enhanced organizational innovation capabilities if it can be successfully leveraged.

However, some recent evidence of discriminatory behavior, e.g., (Ziezulewicz, 2017), in both recruitment and in promotion, has raised a question of whether the existing anti-discrimination practices, primarily predicated on instituting a purely objective 'merit based' system, are serving us as well in the current information age (where information is ubiquitous, change is rapid, and uncertainty endemic) as they did in the industrial age when they were first formulated.

A nuance in our existing strategy for measuring and managing our embrace of diversity, (primarily focused on proportionally reflecting, within the Navy, the general population's distribution of disparaged identity groups), has recently been articulated. That new strategy has been labeled 'inclusion'.

The hope and dream driving the *inclusion* strategy is that if we can create a more 'inclusive' Navy culture, then the historical challenges inherent in the attempt to integrate a culturally and socially diverse workforce might not only be ameliorated but converted into an organizational asset that yields enhanced loyalty (retention), innovation, *and* operational effectiveness.

Though that concept has wide-spread intuitive appeal, a measurable and consequently manageable meaning of an inclusive culture/organization has heretofore defied articulation, for reasons that simply weren't obvious.

This study was commissioned in an attempt to identify the *obstacles* to operationalizing the meaning of an *inclusive* Navy culture and, if possible, to *define* a measurable operationalization that, importantly, would yield the promised benefits of: enhanced personnel retention, improved organizational innovation, and upgraded operational effectiveness to the USN, operating in its unique mission environment.

Finally, if such a meaningful operationalization could be defined, the study was tasked to make recommendations as the nature of programs that could be instituted within the Navy that would facilitate the transformation towards a more 'inclusive' Navy.

Findings and Conclusions

Seven primary findings, ranging from problem clarification to proposed solution, resulted from this study. Each of these is summarized below:

1. Current measures of organizational 'inclusiveness' have limited utility.

A review of the standard processes utilized to measure the current inclusiveness status of Navy organizations and to track their progress over time and/or to compare distinct organizations was revealed to be largely based on surveys of the members of the various organizations.

Standardized surveys such as the NewIQ (annually administered to federal employees) and the 'Inclusion at Work' (occasionally administered to DoD personnel) were found to be the primary basis for existing organizational inclusiveness assessments.

These existing surveys methods were found to be deeply flawed in their capacity to serve their intended measurement function. These problems were revealed to reside in not only serious but remediable methodological issues (primarily involving uncontrolled exogenous influences) but in the assumption that 'organizational inclusiveness' *can* be reliably assessed through constituent member's evaluation of how valued they feel they are to their organization vis-à-vis other members and/or other organizations.

Feeling 'included' (versus 'excluded') was found to reflect, in these surveys, little more than the assessment, of each member, of their value to the organization relative to other members of the organization. As such these surveys are seen to primarily reflect a zero-sum game where intra-organizational and inter-organizational variability are seen to be largely attributable to exogenous factors.

2. Current definitions of inclusiveness are primarily relativistically defined.

At the core of existing definitions of Navy inclusiveness is fundamentally the notion of fairness in one of several forms. At first glance predicating organizational inclusiveness on fairness seems like a reasonable construct.

But a deconstruction of what the Navy means by fairness reveals a network of interrelated challenges in linking a sense of fairness to a sense of inclusion for an organization that operates in the context of limited resources and unpredictable complexity.

The problem essentially boils down to this: The current USN most highly values those of its members who are most willing (i.e., at a cost to their own personal interests) and capable (i.e., physically and cognitively) of serving/supporting the Navy Mission. This 'merit' based assessment of 'value to the Navy' defines, for the Navy, which of its members it truly most highly values and will consequently 'sacrifice' to retain.

The consequent subtle competition, amongst the membership, to define and defend one's 'nobility' (i.e., willingness to sacrifice self-interest) precipitates a difficult (but not impossible) environment in which to make *all* Sailors feel *more* included.

What pragmatically makes the objective of making *all* Sailors feel *more* included is the unpredictability of the requirements placed on and resources provided to the Navy. This unavoidable uncertainty makes even the sense of feeling included as in 'knowing the rules of the game' beyond the reach of the Navy.

3. The changes wrought by the Information Age challenge our traditional notion of inclusion.
Compounding the inclusion problem characterized above is that the Navy's operational environment has, in recent decades, changed. The relatively stable industrial age threat environment has yielded to a much more dynamic *information age* threat environment.

The Information Age environment is characterized by much higher levels of uncertainty and unpredictable in the scale, locus, and strategic focus of external threats and opportunities. Even more challenging is that the internal structure/dynamics of encountered threats (i.e., 'engineered' vs. 'swarming') is not only less predictable but more dynamic.

The result of the emergence of this much more dynamically evolving threat environment is that the role played by the much revered and disciplined *reliability*, at the heart of the Navy's Core Values, in defining who are was securely included and who was not, began to lose it pragmatic utility.

The value in disciplined and self-sacrificing *reliability* is increasingly finding itself in conflict with the multi-scale need to effectively 'innovate' in order to effectively engage the encountered threat.

4. Sensemaking crisis serve as a critical test of organizational inclusiveness.
Nowhere is an organization's capacity to maintain a sense of inclusiveness more sorely tested than in the context of an encounter with a time-sensitive threat that can't be readily comprehended. These sensemaking crises can and often do precipitate severe losses in confidence in the collectively understood plan. And all too readily that loss of confidence, in 'the plan', can trigger an avalanche of lost trust relations, senses of betrayal, and a consequent lingering sense of diminished inclusion.

Recent research has revealed a leading trigger of such sensemaking crises as involving external contexts that require the organization to switch from being 'end oriented' to being 'means oriented' (and/or its reciprocal). These rivalrous (ethical) frameworks (employed to evaluate the organizational felicity of individual actions) are not only mutually incompatible but largely mutually incomprehensible. (Each also defines its own distinct sense of 'nobility'.)

Organizations that are 'emotionally' committed to a specific 'ethical style' of organizing are particularly challenged when their threat/opportunity environment calls upon them to switch styles. Particularly non-adaptive organizations often simply fail to make the adjustment and have been shown to effectively fractionate in a cascading and progressive sense of inclusion loss along with a concomitant, sometimes permanent, loss of organizational effectiveness and innovation.

5. Successfully navigating a sensemaking crisis requires a cultural shift from *nobility* to *adaptability.*
For the Navy to more effectively cope with these critical and increasingly common sensemaking crises will require a cultural shift from its current focus on 'nobility' to one focused on more saliently on 'adaptability'.

The change is not trivial but it is required if the 21st Century Navy of the Information Age is to remain the premier fighting force that it is today.

Foundational to the required Navy cultural change is the need to institute a capacity to be comfortable with uncertainty amongst all Sailors. This embrace of uncertainty, even in the context of collective action, requires the acquisition of a disciplined capacity to suppress more 'instinctual' responses to uncertainty. Yet it is this collective capacity to tolerate uncertainty that lies at the heart of an adaptive organizational capacity to endure the 'identity transforming' consequences of sensemaking crises. Maintaining the dual roles of 'mentor' and 'hero' as described in Campbell's description of the monomyth is provided as a template for the objective Navy Sailor's 'sacred' narrative.

6. Objective measures of social network structure/dynamics are preferred for measuring inclusion.
Assessing the properties of an emergent (social) entity by asking the constituents, from whom these collective properties emerge, about them, has long been recognized as problematic.

[It's a bit like trying to ask an ant about how the colony finds its food or a termite about how they build their mounds; they really don't know. All they really 'know' is that they respond to the pheromones in their environment … (in fact, the very notion that food-gathering optimization or structured mound-building is even occurring is not something the individual ant/termite can cognize).]

The individual constituents of a social organization simply aren't in a privileged position to judge how effective their organization is in making *everyone* feel included … even if they agreed on what the notion might mean (which they don't). *And,* even if organizational inclusion *could* be usefully/pragmatically represented as the mean value of some aggregated subjective assessment, the human need to feel included (i.e., to feel like we 'belong') is so strong that we humans rarely acknowledge that we don't rightfully belong (even when we've been outright outcast), i.e., 'denial' reigns supreme in this domain.

Fortunately, there are a number of tools at our disposal that can be used to *directly* assess and cross-validate these organizational properties without recourse to the subjective, limited, and biased opinions of the organizational membership.

The common feature of the five recommended assessment tools, described in the report, is that they all directly analyze the organization's social network structure and/or dynamics for signs of the adaptivity that we are looking for in a meaningfully inclusive organization.

Some of these tools look at the structural linkages between the various constituents (individuals and/or SIGs) and how they change in response to various stimuli. Others look at the form or content of the information flowing over these links. But their individual and collective efficacy in meaningfully assessing organizational 'inclusiveness' lies in abandoning the subjective survey approach in favor of a direct assessment of the collective social behavior in question.

7. Recruitment Training plus CIP programs offer promise in facilitating the required cultural changes.
The required Navy cultural changes that are recommended as crucial to the institutionalization of a meaningfully more inclusive Navy organization, capable of delivering the promised increase in loyalty/retention, innovation and effectiveness, require significant modification to the core values that we currently instill in our Sailors. Foremost amongst the required additions to the Navy's Core Values is a significant increase in the current emphasis on *adaptability*, especially in the context of *uncertainty*.

The critical elements of this 'adaptability' are delineated, and a hybrid organizational transformation program is defined consisting of recommended modifications to Recruit Training in conjunction with a leadership lead sustaining/enriching Continuous Improvement Program.

Recommendations for Further Research

Further research is recommended to facilitate the recommended Navy organizational transformation. These recommendations fall into two natural kinds: validating the recommended metrics and establishing the efficacy of the enhancement initiatives.

Recommendations are made for funded research directed at refining and validating *each* of the five identified organizational inclusion metrics. Studies should be conducted to substantiate the relation between the refined inclusion metric and the promised organizational benefits (better retention, innovation and effectiveness). These studies are also expected to yield recommendations for conducting 'first order' organizational inclusion assessments in under-resourced (or time-constrained) Navy organizations.

Recommendations are also made for funded research directed at refining and establishing the efficacy of *each* of the four recommended adaptability enhancement methods. Particularly research should be conducted to establish both the immediate *and* longitudinal impacts of each of the interventions.

A particularly strong recommendation is made here to investigate the value of early (and sustained) 'mindfulness/compassion' in facilitating the intended transformation. Early indications of effectiveness, from even fairly limited exposure to these practices, in ameliorating the negative impacts of ACE (Adverse Childhood Experiences) and posttraumatic stress disorder (PTSD) on adaptability provide particular promise in the context of our intent to create a more inclusive, loyal, innovative and effective Navy.

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NPS-18-N071-A: Development and Assessment for Light Weight Virtual Reality Training

Researcher(s): Dr. Kathryn Aten, Ms. Anita Salem, and Mr. John Dillard
Student Participation: MAJ Jeremy Rogers USA, CPT James Sanders USA, and MAJ Adam Vogel USA

Project Summary

This research supports the Navy's Center for Security Forces (CENSECFOR) delivery of ready and relevant learning by providing (1) knowledge of innovative industry practices and technology and (2) recommendations and transition planning based on integration of this knowledge and a comprehensive assessment of CENSECFOR needs. Year One progress includes a student thesis focused on identifying innovative public safety and security forces utilization of and best practices for augmented and mixed reality technologies. The review will result in a detailed, annotated bibliography including results of performance studies, a typology of technology features and uses and recommendations. Second stage research will include a review of human factors issues related to Augmented Reality and a roadmap for acquiring these systems.

Keywords: *augmented reality, mixed reality, wearable computing, public safety, security, military, performance, human factors, usability, acquisitions.*

Background

Augmented reality, virtual reality, and mixed reality are technologies we can leverage to effectively and efficiently provide realistic training to our Soldiers without the high costs involved with mobilizing a unit for combat training. Our research will focus on a survey of currently available technologies in augmented reality, virtual reality, and mixed reality systems; exploring the current training applications available in the commercial, law enforcement, and military law sectors; and identifying any potential issues involved in using these technologies

Findings and Conclusions

The research explores how the military is using augmented and mixed reality technologies, including training simulations, situational awareness, forward observer training, flight crew and pilot technologies, battlefield simulations, military intelligence, embedded training (medical, technical, and maintenance), engagement skills, robotics, and small unit tactics. The thesis also explores law enforcement and public safety applications, including training and operations, for instance patrolling, special weapons and tactics (SWAT), and criminal investigations.
The research team has conducted a detailed literature review and site visit to better understand sponsor needs.

Recommendations for Further Research

Recommendations will include recommendations for acquisitions and human factors integration.

NPS-18-N079-A: Advancing the I-TRAIN Cost Model in Support of Fleet Readiness

Researcher(s): Dr. Robert Eger
Student Participation: LCDR Michael Bell USN, LT Christopher Huizinga USN, LCDR Victor Lange USN, LT Joseph Minnich USN, Capt Travis Neesmith USMC, LCDR Thomas Radich USN, LT William Sczepanik USN, and LT Mark Wilson USN

Project Summary

This report provides an assessment of resource consumption within the street-to-fleet (STF) transformation process. Costs associated with training, scheduling and asset allocation within the training pipeline are estimated using the Installation–Training Readiness Aligned Investments (I-TRAIN) cost model. This report describes how the cost estimation capabilities of the I-TRAIN model may be used to inform decision making in the STF transformation process. The findings of this analysis are presented to fulfill the requirements of the FY 18 NRP I-TRAIN Project.

Keywords: *Cost Model, Assessment, Street-to-Fleet*

Background

Using prior work associated with the I-TRAIN cost model as a platform for total cost assessment, this research explores the throughput dynamics of sailor demand and trade-off decision because of ADP and transformation initiatives. By focusing on the resource sponsor effect due to a changing fleet demand signal, a changing street-to-fleet (STF) transformation process (Block Learning and Ready Relevant Learning objectives), and changing fleet readiness objectives, we provide resource sponsors the opportunity to look at costs impacts associated with these dynamic changes. The information contained in these costs impacts allow decision makers to take into account how changes to flow and throughput effect the entire training enterprise including sailor flow and throughput, scheduling, and asset allocation.

Findings and Conclusions

Objective 1. Assess the cost impact on resource sponsor projected requirements based on variations in the student phasing plans, capacity constraints, a changing demand signal, changing fleet readiness objectives, and a changing STF process. Findings: The primary function of the I-TRAIN model is to track each sub-component of the total cost of the STF process.

Phasing Plans/Changing STF Process: The I-TRAIN model describes the STF process as consisting of six phases. The first three phases are unaffected by the primary policy change under consideration: the shift from legacy to block learning (BL) training. Phase 4, Initial Skills Training (IST), is comprised of various courses that recruits complete. The impact of changes in the phasing plans on any of the cost components can be modeled using the I-TRAIN model.

Capacity Constraints: The I-TRAIN model estimates total costs of providing training to a given number of total recruits. It uses standard assumptions of workforce attrition across the training process. Changes to the total number of recruits, the number of available instructors or other cost components can be evaluated with the model.

Changing Demand Signal/Fleet Readiness Requirements: The model currently uses a given distribution to assign recruits across different rating paths. The model can be reconfigured to address new rating path requirements.

Objective 2. Assess how sailor demand is impacted by student Not Under Instruction (NUI) time. Consider resource sponsor costs and reduced sailor fleet time (due to NUI) for a specific STF Transformation process. Findings: The I-TRAIN model incorporates NUI time in its overall costs of the STF process. This I-TRAIN capability enables decision makers to evaluate scenarios of different resource allocations.

Objective 3. Given a specific cost for a sailor to complete the STF Transformation process, what are the impacts when significant phasing or tempo changes occur? Findings: Using the OS 'A' School rating path as a test case, the costs of processing a recruit through the STF process were calculated with the I-TRAIN model. The cost components identify the parts of the STF process that would be affected by phasing or tempo changes.

Objective 4: Identify the existence of any Commercially Off the Shelf (COTS) programs available that best suits the functionality of I-TRAIN Cost Model? Findings: The I-TRAIN model is currently developed in Microsoft Excel. If this I-TRAIN tool is going to be maintained over an extended period and be employed by multiple users, it is highly recommended that it be redeveloped using such software so that the programming logic is clearly apparent. Additionally, it should be accompanied by adequate training materials. In its current state there is little documentation or notes that would inform the user how to operate the model.

Recommendations for Further Research

It is highly recommended that I-TRAIN be redeveloped using such software so that the programming logic is clearly apparent. Additionally, it should be accompanied by adequate training materials. In its current state there is little documentation or notes that would inform the user how to operate the model.

NPS-18-N320-A: Improving Visibility of Talent: Analysis of Technical Skills and Cognitive Aptitude of Navy Officers

Researcher(s): Dr. Simona Tick, Dr. Mark Nissen, Dr. Jeremy Arkes, and Dr. Elda Pema
Student Participation: LCDR Erik Moss USN

Project Summary
Under the *Sailor 2025*, *Force of the Future*, and *Talent Management* initiatives the Navy is increasing efforts to recruit, develop, assign and retain the most talented officers. On-going research and work supporting the Performance Evaluation Transformation (PET) have tentatively identified several dimensions of talent, or capability. This study aimed to support the efforts to validate the traits identified by the PET working group for use as signals of talent and predictors of high performers.
Keywords: *Performance Evaluation Transformation, Identifying talent and high quality in the Navy, measures of talent integrated qualitative and quantitative analysis*

Background
As acknowledged by CNP in January 2018, the U.S. Navy is in a "war for talent" that requires the modernization of personnel management and training systems to more effectively recruit, develop, manage, reward, and retain a talented manpower.

'Sailor 2025' includes several initiatives aimed at overhauling personnel management policies from promotion and advancement, to evaluations and Fitness Reports (FITREPS), selection boards, educational and other professional development opportunities.

Under this initiative, the Navy is undergoing a Performance Evaluation Transformation (PET), which seeks to correct shortfalls in the legacy system, which include (but are not limited to) the tendency to value tenure over performance, the reverse-engineering of member trait values, the ill-adaptedness of mentoring/counseling and job matching functions of the tools and processes. In undergoing this transformation, the Navy aims to take advantage of state of the art tech tools, more accurate metrics and more robust social science practices to improve system efficiency and effectiveness in personnel management and to instill confidence in the process and the tools from the leadership levels to the deck plates. The third PET pilot is ongoing, followed by phased implementation. Validation and implementation requires effective talent identification and assessment. This study aimed to support the efforts to validate the traits identified by the PET working group for use as signals of talent and predictors of high performers.

Findings and Conclusions
To support Navy leadership decision-makers' efforts to identify and measure talent, our study used an integrated quantitative and qualitative approach.

The qualitative part of the study included an effort to integrate the previous two investigations toward understanding talent in the US Navy more broadly. Previous work by Nissen and Tick (2017) focused on the Navy Information Warfare (IW) Community, while Nissen and Tick (2018) focused on the Surface Warfare Community (SWO). Both studies have been enlightening and informative, and we have a much better understanding now, both of what talent means in each community and what steps are important for retaining our talented officers in each. Indeed, we find *talent* to represent a situated and nuanced concept, with key characteristics differing across ranks, roles, jobs and other factors that also vary over time. Hence, it has been uncertain whether the talent we retain is the best to meet our present, much less our future, needs.

In this present study, we continued to integrate a quantitative approach with our qualitative approach to increase the visibility and understanding of talent in the US Navy. Using personnel data on naval officers commissioned between 1999 and 2003 and followed annually until promotion to O4 or until separation, the quantitative study aims to determine job relatedness and performance indicators of legacy fitness report scores. In our study, we looked for alternative measures that can indicate a high performer as predicted by the legacy fitness report scores that establish job relatedness and performance. Fitness reports can differentiate officers' performance via individuals' trait scores and via promotion recommendations by the Reporting Senior. We used fitness report scores to build performance indexes and to test their power to predict performance of naval officers later in their career. This is especially important, as the new performance evaluation system will reward the potential of future capability versus past performance. By using a five-year period, we captured information from a series of annual performance reviews that covered a variety of jobs and supervisors. We were able to propose and validate alternative measures of past performance to identify officers who are likely to be high performers in the future.

The findings from the integrated qualitative and integrative study confirm the situated and nuanced nature of talent, but they also highlight common elements across the two communities studied. These common elements may prove insightful for understanding and retaining talent across the US Navy.

Recommendations for Further Research

Given the tight competition for talent, the Navy could benefit from a better understanding of how different talent markers differ by community, and how to seamlessly transition from the legacy to the new evaluation system in a way that rewards, mentors, trains and retains the most talented, high quality personnel. Follow on studies can use multivariate statistical analysis combined with the most current qualitative research methods to identify which elements from the legacy FITREP system measure 'past performance', and which elements measure 'future potential'.

Another direction for a future study is to consider an integrated qualitative and quantitative approach to investigate the relation between dissemination of the Navy Desired Leader Attributes (NDLAs) used to identify expected character qualities, behaviors, and skills, as markers of talent, and the officers' performance. What is the relation between dissemination of the Navy Desired Leader Attributes (NDLAs) and the officers' performance? What are the counseling, mentoring and coaching needs to develop the officers' potential and generate quality? The follow on study could use qualitative methods to identify counseling, mentoring and coaching needs to develop the officers' potential and generate quality.

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NPS-18-N185-A: An End-to-End Big Data Application Architecture for the Common Tactical Picture

Researcher(s): Dr. Magdi N Kamel
Student Participation: No students participated in this research project.

Project Summary
Big data is opening up new opportunities for organizations to gain insight and make intelligent inferences from huge volumes of data in real time and across multiple data sources. All these disparate sources of data need to be managed in a consolidated and integrated manner to get valuable inferences and insights. The architectures for realizing these opportunities are based on relatively inexpensive and heterogeneous infrastructures than the traditional monolithic and expensive options that exist currently. Selecting the right architecture is crucial to harnessing the power of big data. However, heterogeneity brings with it multiple options for solving the same problem, as well as the need to evaluate trade-offs and validate the "fitness-for-purpose" of the solution.

The goal of this research is to propose an end-to-end application architecture for the Common Tactical Picture and Combat ID that ensures that all essential components required to collect, store, analyze, and visualize all aspects of the big data set are present. The elements of the proposed architecture include a data sources layer, an ingestion layer, a storage layer, a physical infrastructure layer, a platform management layer, an analytics engine layer, a visualization layer, a security layer, and a monitoring layer.

Keywords: *big data, end-to-end application architecture, big data ingestion, big data management, big data storage, big data analytics, big data visualization*

Background
Big Data Architectures and Analytics (BDAA) can address Common Tactical Picture (CTP) and Combat ID (CID) challenges that include unsupervised learning, self-taught learning, deep learning, pattern recognition, anomaly detection and data fusion. Study of architecture approaches and choice of analytic tools is required to optimize BDAA to support Common Tactical Picture Naval Integrated Fires and Combat Identification applications across warfare areas.

BDAA has significant potential to contribute to Combat Identification, the Common Tactical Air Picture (CTAP), and provide input to future Battle Management Aids (BMA) for Integrated Fires, including Naval Integrated Fire Control – Counter Air.

The objective of this research project is to propose a BDAA which can provide one common, consistent data stream of CTP and CID data to serve every information consumer.

Findings and Conclusions
This research outlined a methodology for developing a big date architecture by defining and detailing each component of the underlying architecture as it pertains to the CTP and CID problems. The following is a summary description of each component of the architecture.

Data Sources Layer
The main challenge with defining a big data solution begins by identifying the internal and external data sources of different volumes, velocity, and variety to be included in the big data set to be analyzed. These big data sets, also called data lakes, are pools of data that are tagged for querying or searched for patterns after they are stored in the big data stack.

Ingestion Layer
This layer loads relevant information from internal and external data sources, after removing the noise, to the big data storage layer. The ingestion layer includes capabilities to validate, cleanse, transform, reduce, and integrate the data into the big data stack for further processing.

Distributed Storage Layer
This layer uses massively distributed and parallel processing and storage to execute over the big data set. This distributed processing and storage layer provides scalability, availability, reliability, fault-tolerance, and parallelization. The Hadoop distributed file system (HDFS) is the cornerstone of the big data storage layer. This layer also includes Non-Structured Query Language (*NoSQL)*, or *not only* Structured Query Language (*SQL)*, databases. These are distributed, non-relational data stores designed to support large volume and variety of data and include key-value pair, document, graph, columnar, and geospatial databases.

Physical Infrastructure Layer
The physical infrastructure layer supports the storage layer. It is based on a distributed computing model by physically storing and processing data on multiple servers linked through a network and a distributed file system. By using a "share nothing" architecture, network traffic is minimized since data is no longer transferred to a monolithic server to process it.

Platform Management Layer
This layer provides the tools and query languages to access the data in the NoSQL databases using the HDFS storage file system sitting on top of the physical infrastructure layer. The platform management layer accesses data, runs queries, and manages the lower layers using scripting and SQL-like languages.

Analytics Engine Layer
This layer provides the tools to extract valuable insight from huge volumes of data across the big data stack. The insights obtained from data are used to recommend action or to guide decision making in the domain of context. The analytics can happen on both the traditional data warehouse or on big data stores.

Visualization Layer
The visualization layer provides means to communicate information clearly and efficiently using statistical graphics, plots, information graphics, and other tools.

Security Layer
The security layer is responsible for protecting the data from unauthorized access, modification and/or destruction, and limitations on availability. Security has to be implemented in a way that does not harm performance, scalability, or functionality, and it should be relatively simple to manage and maintain. Security requirements have to be part of the big data architecture from the get go and not as an afterthought.

Monitoring Layer
The monitoring layer provides tools that help monitor all components of the big data stack. The monitoring system has to be aware of different hardware and operating systems using high level protocols like eXtensible Markup Language (XML) instead of binary formats that are machine

dependent. Performance is a key parameter to the monitoring layer so that there is very low overhead and high parallelism.

Recommendations for Further Research

The effort of this research developed an end-to-end application architecture for the Common Tactical Picture and Combat ID that defined the application architectural components required to collect, store, analyze, and visualize the big data set. We recommend that future efforts develop a proof-of-concept pilot prototype based on the proposed architecture. This requires the following activities:

1. A thorough identification of all internal and external data sources to be included in the big data solution including the frequency, volume, velocity, type, and veracity of the data
2. A detailed specification of the ingestion layer requirements to validate, cleanse, transform, reduce, and integrate the data into the storage layer for further processing
3. A detailed specification of the distributed storage layer and physical infrastructure layer components
4. A specification of the tools, NoSQL databases, and query languages to access the data in the big data stack
5. Identification of the type of analytics to be applied for processing data (e.g., predictive, analytical, ad-hoc, etc.) and the type of visualization of the results from analytics

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NPS-18-N013-A: Reinforcement Learning for Modeling Large Scale Cognitive Reasoning (Phase II)

Researcher(s): Dr. Ying Zhao
Student Participation: Capt Jennie Bellonio USMC

Project Summary

In related research we demonstrated that big data (BD) techniques and analytics can provide potentially useful information in assisting the combat identification (CID) problem and improving the CTAP (Common Tactical Air Picture). CID is notoriously a very difficult function, often more art than science process is still very manual, and decision makers can experience cognitive overload so analytics is just one aspect of CID. CID would then be a good case study to investigate machine learning and artificial intelligence (AI). The focus of our research has been the question: Are machine learning (ML) and artificial intelligence (AI) systems able to learn and use the existing knowledge models for better and timely decision making for CID? Soar is an open source tool as a cognitive architecture, developed by the University of Michigan. Expert systems include reinforcement learning (Soar-RL). We first used Soar with a thesis student who was a Tactical Action Officer (TAO) that represented the "teacher", and we empirically showed that learning did take place in Soar. We then began using a Soar version which is integrated into Naval Simulation Software (NSS) as an agent to further aid in the CID decision making process, and eventually offered the opportunity to integrate real world data into the process. We also used LLA (Lexical Link Analysis) that provided initial learning rules to Soar. LLA is an unsupervised deep learning tool that can discover the correlations among the attributes, and therefore is used to discover the initial rules for NSS and Soar-RL. Our research empirically answered our core question that the ML/AI method, a.k.a. the Soar-RL integrated with LLA, can learn and use the existing knowledge models for better and timely decision making for CID. We saw error rates go from 3.7% to 0.4% with initial rules provided by LLA.

Keywords: *combat identification, reasoning, reinforcement learning models, rule-based AI*

Background

NSS has capabilities for simulating sensor data fusion and tactical naval platforms and systems to model the formation of situational awareness and the engagement kill chain. In real operational situations, the amount of data and information coupled with the complex decision space can overwhelm operators and commanders' cognitive abilities in the tactical decision loop. The current naval simulation framework does not address the cognitive layer that is critical to warfare effectiveness assessment from a system of system perspective. The cognitive functions include: decision making, sensor fusion and analytic processes (and workflow), for example, in a kill chain in an integrated fires environment, are very complex. The current NSS does not have the ability to model, understand, and optimize the complicated decision-making processes and cognitive functions required in a realistic operational scenario, such as a tactical kill chain. A critical modeling gap is the analytic process and reasoning leading to decisions from the situational awareness provided by the common operating picture.

The Soar cognitive architecture (developed at the University of Michigan and used by Soartech) is a well-known modeling tool and has applications in this field including an implementation of reinforcement learning (Soar-RL). The Soar engine has been integrated into the NSS and has been licensed to the Naval Postgraduate School (NPS) as the Warfighting Impact of Simulated Decision Makers (WISDM). This project's objective is to develop Soar agents in NSS to model the reasoning (using Soar production rules) through knowledge systems, rules, heuristics, and NSS simulation data. Developing a cognitive model and architecture to represent a realistic warfighting decision process will enhance the Navy's ability to understand and analyze the kill chain and improve automated decision aids and human-machine-interfaces. This year, the challenge we found was that the parameters in the Soar-RL do not converge. We researched the reasons using an alternative initialization of the parameters in Soar-RL and learning-rate decay method (alpha decay) method to address this challenge.

Findings and Conclusions

Our core research question: Are ML and AI systems able to learn and use the existing knowledge models for better and timely decision making for CID? If yes then the corollaries would be whether such a system learn from:

- the historical data with ground truth (Task 1)
- feedback of a human operator (Task 2)
- cross-validation of big data (Task 3)
- the delayed ground truth after actions taken (Task 4)

The NSS generated simulation is to address Task 1.

We made the following advancements as listed below:

- Advancement 1: Developed LLA to discover the initial rules for Soar-RL
- Advancement 2: Developed LLA to compute the initial preferences for Soar-RL
- Advancement 3: Modified Soar-RL to the alpha-decay (learning-rate decay) for the reinforcement learning algorithm to learn the parameters (i.e. the preferences) so the error rates converge as more iterations of the data
- Advancement 4: Compared the Soar-RL with zero initial preferences and the LLA initial preferences with different initial learning rates and ε -greedy strategies, where ε is the degree of randomness in the Soar exploration.
- Advancement 5: Compared the Soar-RL with other predictive methods such as logistic regression, decision trees, and nearest neighbors. Concluded that the Soar-RL generates comparable results with the advantages of being an on-line learning, rule-based, and AI explainable system.

The details about advancements are documented in the paper [2].

Recommendations for Further Research

We are applying the methods developed to the realistic data such as re-constructions and re-play the tracks from a Collaborative Engagement Capability (CEC) exercise event to demonstrate self-learning and a mission planning application named a multi-segment online war gaming/simulation leveraging AI.

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NPS-18-N094-A: Cognitive Threat Emitter Recognition of Behaviors with Deep Neural Networks

Researcher(s): Dr. Neil Rowe, Noboru Schwamm, and Mr. Bruce Allen
Student Participation: Pawel Kalinowski

Project Summary

We were tasked to assess the suitability of deep-learning methods for complex high-frequency signals such as were produced by recent automated underwater vehicles. Such vehicles transmit detailed data that is considerably more complex than traditional sensors. We interpreted the task as including several subgoals. First, we need to determine distinctive features of these signals. Second, we need to distinguish different signal sources from each other. Third, we need to distinguish periods of time within those signals and make guesses as to what is happening in each. We used an approach of extracting features from both the time domain (wavelets were the most helpful) and the frequency domain (logarithmically spaced frequency components were the most helpful). We trained several kinds of machine-learning models and demonstrated excellent performance in distinguishing the test signals.

Keywords: *combat identification, aircraft, ships, big data, distributed processing, anomalies, machine learning*

Background

Signals produced by autonomous vehicles can be complex. They use a wide frequency range and show frequent intermittent activity. Their complexity however does provide a variety of distinctive features that can be recognized and matched to historical data to identify the vehicle and what it is doing.

Findings and Conclusions

We received three samples from the sponsor of 20 seconds each. The data was quite bursty, with predominant periods of minimal activity interspersed with periods of intense activity. Gaps between larger periods of activity were irregular, but patterns were clearly in the range of microseconds. Gaps can be found as either abrupt changes in the level of signal energy or abrupt changes in the cosine similarity of the frequency distribution. The first was found to be more reliable.

The best techniques we found for this data were to extract strong matches to Haar wavelets applied to the signal-energy function, and to measure components at 10 specific higher frequencies evenly spaced logarithmically. To find the best techniques we ran a number of tests that varied parameters. Signal energy appeared to be more helpful than the raw signal, Haar wavelets at higher frequencies were more helpful than those at lower frequencies, and trigrams of strong wavelet matches within a time period of 0.001 second were better than unigrams, bigrams, or quadgrams. Experiments showed that most of the useful frequencies were at 100 kilohertz or above, though one of the signals had significant lower-frequency components. The useful frequencies had a considerable range, so logarithmically spaced components were necessary.

We were tasked to distinguish the signals. This can be done by either comparing n-grams or frequency components. There were few exact n-gram matches, since n-grams can be characterized by the strengths of the wavelet matches and their spans and these are float-point numbers. So, we found it best to compute the maximum cosine similarity for each 65536-sample segment of one signal to the segments of the other signal. Two of the signals were considerably more difficult to distinguish than the other two pairs, so machine-learning techniques were suggested. Unfortunately the amount of data was inadequate for deep-learning techniques. Distinctive features in both the time domain and frequency domain were on the order of 100,000 for each signal, but deep learning requires billions of cases to train on. So, we tested other forms of machine learning that did not require so much data, including a Naïve Bayes, random decision forests, K-nearest-neighbors, and shallow neural networks. Performance was good for all of them (generally over 99% accuracy), but the small size of our sample limited our training ability. Additional experiments with a neural-network approach on our NPS Hamming/Grace supercomputer demonstrated that its multiprocessing environment could speed up processing time considerably.

Recommendations for Further Research

Future work should involve testing with real data, and should include a variety of additional platforms such as land vehicles and drones.

NPS-18-N193-A: Big Data ML and AI for Combat ID and Combat Systems – Design, Demonstrate and Proof of Concept

Researcher(s): Dr. Dan Boger, and Dr. Ying Zhao
Student Participation: No students participated in this research project.

Project Summary
The project concerns two concepts for naval warfighting: common tactical air picture (CTAP) and combat identification (CID). The CTAP process collects, processes, and analyzes data from a vast network of sensors, platforms, and decision makers and provides situational awareness to air warfare decision makers in a kill chain process. The CID process locates and labels critical airborne objects (as friendly, hostile, or neutral) with high precision and efficiency based on a CTAP as part of the core kill chain process. The existing methods of CTAP and CID involve wide ranges of participating platforms, such as destroyers, cruisers, carriers, fighter attack aircraft and tactical airborne early warning aircraft; participating sensors, such as Radar, Forward Looking Infrared (FLIR), Identification Friend or Foe (IFF), Precision Participation Location Identifier (PPLI), and National Technical Means (NTM); and Participating Networks and Systems, such as the Aegis combat system, Cooperative Engagement Capability (CEC), and Link-16.

CID is notoriously a very difficult function, often more art than science process is still very manual, and decision makers can experience cognitive overload, so analytics is just one aspect of CID. Challenges in the CID process include (1) extremely short time for fusion, decision-making, and targeting; (2) uncertain and/or missing data outside sensor (e.g. radar, radio) ranges; (3) manual decision-making; (4) heterogeneous data sources for fusion and decision-making; and (5) multiple decision-makers in the loop. The CTAP and CID problems can be seen as both big data and no data. On one hand, the data used for CID comes from a combination of massively cooperative and non-cooperative sensors, organic sensors, and non-sensor information (where, typically, each sensor collects certain attributes). The big CID data then needs to be fused over time and space since they are collected in a distributed fashion. On the other hand, adversaries often conceal and change their true intentions, therefore rare or no data are observed for analyzing anomalous and adversarial behavior. Therefore, the CTAP, CID, and kill chain problems are challenging application areas for analytic, machine learning (ML), or artificial intelligence (AI) methods.

In the past, we demonstrated that big data techniques and deep analytics can provide potentially useful information assisting the CTAP and CID. Big data (BD) techniques allow the distributed acquisition and fusion of disparate and crucial combat data in real-time or near real-time. This year, we made advancements as follows:

- We investigated specifically the Defense Information Systems Agency (DISA)'s Big Data Platform (BDP). BDP is designed for real time processing of big data beginning at ingestion and ultimately presenting useful data visualizations that may alert decision makers for anomalies.
- We analyzed the Automatic Dependent Surveillance-Broadcast (ADS-B). ADS-B functions with Global Positioning System (GPS) satellite, rather than radar technology, more accurately observe and track air traffic. Aircraft equipped with an ADS-B Out transmitter sends position, altitude, heading, ground speed, vertical speed, call sign, and other aircraft information to a network of ground stations that relays the information to air traffic controllers and other aircraft. Our work in progress applies various big data, and deep learning including ML/AI tools to predict if a flight is commercial or military.

Keywords: *combat identification, big data, Dependent Surveillance-Broadcast, pattern recognition, anomaly detection, reinforcement learning, virtual airways, DISA's Big Data platform*

Background

ADS-B functions with GPS satellite, rather than radar technology, more accurately observe and track air traffic. Aircraft equipped with an ADS-B Out transmitter sends their position, altitude, heading, ground speed, vertical speed, call sign, and other aircraft information to ground stations that relays the information to air traffic controllers and those who have ground ADS-B receivers. Pilots of aircraft equipped with a receiver for optional ADS-B receive traffic and meteorological information. Aircraft operating in most controlled U.S. airspace must be equipped for ADS-B Out by January 1, 2020[1]. With ADS-B operational across the country, pilots in equipped aircraft have access to air traffic services that provide a new level of safety, better situational awareness, and more efficient search and rescue. An aircraft can be identified by radar transponder identification, friend or foe (IFF) modes such as one, three, and five (military). This is done by Line of Sight (LOS) air traffic control ground radar stations. For improved (cooperative) surveillance for flight separation and control an aircraft can have an ADS-B Out system to broadcast its identification and location from the aircraft's GPS to LOS receiving ground stations and other aircraft (around a 150 mile range). According to International Civil Aviation Organization (ICAO), a.k.a, the international "Federal Aviation Administration (FAA)", states that notable outcomes of using ADS-B include a new frequency allocation for space-based ADS-B reception, enabling tracking of aircraft globally including remote and polar regions.

Our goal is to build ML/AI models such as Lexical Link Analysis (LLA) and reinforcement learning (RL) algorithms to rapidly and accurately classify military and commercial aircrafts based on kinematic characteristics [3]. One way investigated is how the track data could be represented as images and fed into the deep learning algorithm such as convolutional neural networks (CNN) for high classification accuracy [4].

Findings and Conclusions

Advancement 1: We investigated specifically the DISA's BDP[5]. BDP is designed for real time processing of big data beginning at ingestion and ultimately presenting useful data visualizations that may alert decision makers for anomalies. BDP is a complex mix of mostly open source using a variety of programing languages. These include PostgreSQL, pgAdmin4 v2, WinSCP, Putty, Apache Maven, Apache Spark, Apache Spark SQL, Apache Storm (Kronos), Hadoop, Map reduce, bash and Unix commands, yaml and xml files, JSON files, Java files, Querying with JEXL Syntax, GEM prospector, Kafka, RDA Deployer, Accumulo, IronHide (Kibana), git bash, Elastic Search, Zookeeper, Kryolibrary, Citadel, NodeJS, Slider, Analytic-Focused Datasets (AFDs), R-Shiny, and Airflow, and soon it will include Zepplin.

Advancement 2: We analyzed the Dependent Surveillance-Broadcast (ADS-B) which will eventually provide world-wide kinematic data for commercial and general aviation. ADS-B, broadcasts ID and location, and supports separation assurance and traffic flow management according to the FAA Order 8200.45. ADS-B can be used to establish commercial flight baselines and virtual airways, eliminate *neutrals* as much as possible for CID. We downloaded ~4T ADS-B data (6/2016-7/2017, worldwide every minute, 1440 files each day, 6MB each, JSON format). We used big data to train ML/AI models capable of discovering patterns, rules, and anomalies; predicting CID and aircraft types using kinematic characteristics; and performing reinforcement learning and adaptation based on reward feedback. The methodologies about advancements are documented in the paper [3-5].

Recommendations for Further Research

We are applying the methods developed to build a demonstration on a realistic data such as re-construction and re-play the tracks from a Collaborative Engagement Capability (CEC) exercise event to demonstrate reinforcement learning, online learning, and adaptation.

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NPS-18-N193-B: Planning Big-Data Distributed Processing for Combat ID

Researcher(s): Dr. Neil Rowe, Mr. Arijit Das, and Mr. Bruce Allen
Student Participation: Mr. James Zhou CIV, LT Andrew Sollish USN, and Mr. Abram Flores CIV INT

Project Summary
Combat identification (Combat ID) of aircraft and ships is an important problem for militaries. Aircraft in particular move quickly, may not aid identification, may be subject to system malfunctions, or may be misconfigured. Identification is also becoming more difficult because commercial vehicles are less often in air lanes, and we now have autonomous aircraft in the air on nonstandard routes. We now have basic information about most major aircraft from satellite coverage, so combat identification today is a big-data problem. Even if we have facilities to handle large amounts of data, often we have a limited bandwidth to transmit sensor data to them. Our strategy is to push some of the processing and intelligence "to the edge" or to the platforms that collect data. We are developing methods whereby important data can be identified at an early stage. We have identified 16 factors which should be reported when they have anomalous values such as speeds, altitudes, counts in particular areas, deviations from tracks, and mixes of aircraft types in an area. Full data will still need to be transmitted eventually, but early forwarding of time-critical information could help neighboring platforms if we can identify it. We show some results from a prototype implementation using a sample of 110 million records from the ADS-B database. Results on a Hadoop distributed-processing system show speedups of 2-70 over a single-processor implementation depending on the subtask, which says this problem is well suited for distributed big-data methods.

Keywords: *combat identification, aircraft, ships, big data, distributed processing, anomalies*

Background
Combat ID has been a key problem for militaries for a long time. Identification of aircraft in particular can be difficult because they move quickly and may not provide cooperative identification. We do have basic information about aircraft from extensive radar and satellite coverage since this is important for air traffic control. Much of this is available for every second or better. So the key problem with combat identification today is that we have too much data. Sensor reports from nearby platforms combined with satellite imagery can provide too much data to

analyze in time-critical situations. Even if we have big-data facilities available to process the large amounts of data we have, often we have a limited bandwidth to transmit it from sensors to the facilities.

Findings and Conclusions

Centralization of combat ID data taxes bandwidth, and a central node is a single point of failure. Our strategy is to push much of the sensor data evaluation "to the edge" or to the platforms that collect data. If interesting data can be identified at an early stage, this can markedly reduce our bandwidth requirements. Full data will still need to be transmitted eventually, but our main focus is time-critical information that could help neighboring platforms. For instance, aircraft heading out from a base want to know what the last friendly aircraft in that area saw.
We have identified 16 factors which should be reported when they have anomalous values such as speeds, altitudes, counts in particular areas, deviations from tracks, and mixes of aircraft types in an area. We also developed a way to identify anomalous clusters of data. We also extended these methods to detect anomalous ship data. Full data will still need to be transmitted eventually, but early forwarding of time-critical information could help neighboring platforms if we can identify it.

We did two prototype implementations. One used a sample of 110 million records from the automatic dependent surveillance—broadcast (ADS-B) database, and used single-processor programs that we wrote in the programming language Python. This program took around 10 hours for detection of anomalous data records and 15 hours for clustering and anomalous-cluster detection. The other implementation used a different sample of 1.53 billion records from the ADS-B database, plus 6 million ship records. This implementation used Apache Spark technology with Hadoop distributed processing on 3000 cores. This implementation showed speedups of around 100 over the single-processor implementation depending on the subtask, which says this problem is well suited for distributed big-data methods.

Recommendations for Further Research

Future work should involve testing with real data, and should include a variety of additional platforms such as land vehicles and drones.

NPS-18-N196-A: Future Combat Systems – Data and Information Science Technologies as a Force Multiplier

Researcher(s): Dr. Shelley Gallup, and Dr. Mark Nissen
Student Participation: No students participated in this research project.

Project Summary

This research project developed and applied a new methodology for understanding the needs and performance of networks to do work. Networks are now considered a warfighting platform and have increased in performance, complexity and importance. Currently the work intended through the use of networks may not be well described by the engineering performance of hardware and transport layers alone. Instead, we propose that performance is also related to the dynamics of knowledge sharing amongst the actors in the network. In this research, we used emerging constructs of knowledge dynamics to describe and analyze knowledge flows. To test this methodology, we looked at knowledge flows in a tactical situation, in the act of distinguishing friendly tracks from hostile or neutral ones (combat ID, or CID). A simulation is used to show how knowledge flow parameters may be used to help define network requirements and to assess network performance and further, how including new information technologies and data treatments amplify the utility of combined networks.

Keywords: knowledge flows, knowledge simulation, knowledge dynamics

Background

Given Kurzweil's "law of accelerating returns," evolution of computer and information producing technology and its transport is being surpassed now by the next phase of the digital revolution—an addition to the new paradigm, the means to make sense of enormous amounts of data. Indeed, along with artificial intelligence (AI), "big data" techniques are one of the areas of greatest investment for data and information science. In this view, as technology advances, the ability to harvest, store, forward and process enormous quantities of data are combined with automated processing, decision making and the advanced means to distribute. Distribution and sharing data, information and knowledge amongst multiple nodes are the building blocks of networks.

We are quickly approaching the point at which our current, hardware-centric approach to defining warfare needs will become inadequate. Even today, legacy combat systems are unable to handle the torrential flows of knowledge and information required for combat efficacy, and even worse, the current manner in which such systems are specified, designed, integrated and tested fails to address the kinds of flexible, composable, systems of systems that will be so critical for combat when these future systems finally become operational.

The network itself is becoming the relevant "weapons platform," capable of supporting decision makers in future conflicts where fast, reliable flows of knowledge and information comprise the critical edge required for success. However, it is critical to reexamine how future combat systems have their requirements specified, how they are designed and integrated, and how they are assessed to support both human and machine decision makers in future conflicts. Digital and information warfare capabilities will be key to future conflicts, and they need to integrate seamlessly into future combat system designs. The current process is inadequate for the task.

The intent of this project was to examine how network-centric models and methods—which principally support the design and development of information systems—can be integrated with knowledge-centric models and methods—which principally support people and machines making decisions and accomplishing work—to develop more appropriate approaches to combat system specification, design, integration and testing. By focusing on how performance enabling knowledge and information flows through human-machine teams, one can escape the kind of hardware-centric, engineering design practiced today, and through state-of-the-art techniques for the visualization, analysis and measurement of dynamic knowledge and information, we have the ability to assess, measure and compare the efficacy of future combat systems while they remain in the requirements development stage.

Our theory is that this novel, system of systems engineering approach offers much better potential to develop systems capable of fully supporting information and digital warfare approaches that are critical to success in future combat environments. The study proposed here can take a definitive step in that direction.

Findings and Conclusions

This project is not yet complete; however some initial results include the further development of a system of equations that come from physics as an analogy to constructs in knowledge dynamics. Examples are knowledge work, power, energy, distance and time. Data collection was first intended to be obtained in-situ with Tactical Action Officers (TAO) engaged in interactions with unmanned assets in a realistic at sea exercise. A hurricane in the vicinity of the exercise made this approach impossible. A re-set has since been formulated in which a real world scenario is presented to TAO's in an education setting, and obtaining expert knowledge about what knowledge, or in some cases raw information is being provided, and through what sources in a combat identification problem. This will form the context and input data from which the final model will be created, and findings produced for a final report.

Recommendations for Further Research

Knowledge as a resource in creating tactical advantage, in many situations, is needed. For example, Navy Surface Warfighting Development Center (NSWDC) Dahlgren is creating Mission Level Architecture Engineering (MLA&E) which brings together all of the elements of a mission thread in an engineering view. We believe those engineering threads should incorporate knowledge flow dynamics as a means of comparing threads apart from just the engineering details. Additional research is also needed in implementation of knowledge flows in manned-unmanned scenarios.

NPS-18-N264-A: GEOINT Small Satellite Constellation Study for Maritime Domain Awareness

Researcher(s): Dr. James H. Newman, Mr. Charles Racoosin, Mr. Giovanni Minelli, Mr. James Horning, and Mr. David Rigmaiden
Student Participation: LCDR Rhett Begley USN, LT Niki Crawford USN, LT Jeremy McGowan USN, and LT Robert McClenning USN

Project Summary

This executive summary combines the work of three theses that researched the feasibility of a small satellite (SmallSat) constellation to increase intelligence, surveillance, and reconnaissance (ISR) in support of Maritime Domain Awareness (MDA). The three theses each focused on one area of a space systems architecture: orbit and constellation; command, control, and communications (C3); and payload sensor and processing. In addition to these three theses, research was also conducted through a directed study effort into the most efficient means of deploying this notional constellation.

Our research revealed that no commercial satellite architecture is currently available for leverage, therefore a purposed-built constellation is recommended. A constellation of 180 SmallSats using an Electro-Optical (EO) sensor payload can provide the revisit and resolution needed to meet sponsor requirements. At the time of this study, current C3 and image processing capabilities do not meet project requirements. A cross-linked C3 architecture shows more promise than a ground-based architecture, but no such architecture currently exists. While the technology exists to support the ultimate objective of minimize the time between tasking the system and disseminating the data to the end user, the varying maturity levels of these technologies do not currently support on-orbit processing. With currently available technology and taking cost, the number of satellites per launch, and launch tempo into consideration, the Falcon 9 is the recommended platform to deploy this constellation. Potentially, the entire constellation could be placed into orbit in six launches over the span of two to three months, costing roughly $372M.

Our recommended course of action is to invest further research in command, control, and communications; payload sensor; and processing. C3 requires more investigation to identify the optimal system to support the desired constellation's revisit and resolution. The Electro-Optical (EO) sensor restricts imaging to daylight hours, but we recommend researching the potential use of other sensor types such as infrared (IR) or synthetic aperture radar (SAR) for increased imaging opportunity and timeliness. We also recommend further research into automated target recognition because while processing using artificial intelligence (AI) to conduct basic recognition within an image exists, the technology of AI is not mature enough to be completely automated and provide the detailed vessel classification desired by the sponsor. Future research into the optimization of the constellation and launch pattern, as well as the development of smaller launch vehicles with rapid launch tempo capabilities, is also recommended.

Keywords: *artificial intelligence, small satellite, constellation, EO, MDA, SAR, space systems, dark vessels*

Background

Planet Labs, BlackSky, Adcole Maryland Aerospace, and UrTheCast own high-resolution small satellites capable of EO (Crawford, 2018). While these SmallSats demonstrate feasibility of an EO SmallSat constellation, none of these spacecraft are in constellations that provide the necessary revisit for MDA, which is typically less than 30 minutes. For example, Planet Labs' constellation provides daily revisit using a constellation size of 185 satellites (Products, n.d.) and BlackSky provides 90-minute revisit with its planned 60-satellite constellation (BlackSky Transform EO, 2016). Therefore, a purpose-built constellation was designed to meet revisit needs for desired latitudes that are representative of regions often transited by many shipping lanes.

The overall responsiveness of a constellation is affected by the Tasking, Collection, Processing, Exploitation, and Dissemination (TCPED) process. Of these, the collection, processing, and exploitation aspects, to a certain extent, will occur onboard the satellites, but the tasking and dissemination requires a robust C3 architecture. The C3 architecture required to maintain numerous satellites in a Low Earth Orbit (LEO) constellation is more difficult because the required sensor resolution dictates a low orbit which limits the time in view of a LEO satellite relative to a point beneath it on the Earth's surface. The altitude determines the time in view for communications (from the ground) as well as the field of regard (FOR) within which a sensor can be pointed. To achieve the desired resolution with an EO sensor (within a small satellite form factor) implies a very small instantaneous sensor field of view (FOV) which must be pointed within the FOR. This requires a priori knowledge of the expected target's general location and a C3 path to task the sensor. To achieve the desired timeliness, with LEO satellites, means that many satellites are required. Therefore, the C3 architecture needs to provide continuous, or reliable ad hoc, communications to either all of the many satellites, or to those which are approaching the region of interest and which need to be tasked. Using a direct to ground design would require a large number of ground stations in order to both receive data and perform the Telemetry, Tracking and Command (TT&C) mission; Planet Labs uses 30 ground stations for their massive constellation (Orbit Operations, n.d.), and Spire Global uses 30 ground stations to support 57 satellites (Cappaert, 2018), for example. Satellites could instead transmit the data to a satellite outside of the constellation as a relay to the ground. Alternatively, the satellites could cross-link to one another, so each satellite acts as a relay satellite for one another in the constellation.

The processing aspect of the mission architecture is inextricably linked to the C3 architecture given the current state of technology, where satellite imaging payloads mostly operate in a store-and-forward mode. The satellite captures the image of interest, and then when it can establish a connection to a ground site to link to, it sends the data. The use of Field Programmable Gate Array (FPGA) technology has garnered recent attention for use in software-defined radios (SDRs) for SmallSat communication systems (Varnavas, n.d.). For image processing, using FPGA SDR technology on board SmallSats would allow for on-the-fly, overhead programming capabilities (Mcgowan, 2018). This allows more flexibility for SmallSats to upgrade to new algorithms, for example, which would help with offloading processed data to ground sites and the user to meet MDA needs.

Potential launch solutions were down-selected from 24 identified platforms using the following criteria: the ability to carry one to two planes, or 10 to 20 satellites; the ability to deploy the entire constellation for less than $1B; and the number of launches required. The remaining launch platforms were then analyzed for specific orbital maneuvers to determine the minimum number of launches required, the cost, and the estimated launch tempos for each feasible solution. In the launch analysis, we assumed that every upper stage will reach 500 km altitude with the advertised payload capacity; that all of the fuel on the upper stage will be expended; that the available mass-to-orbit only counts toward payload fuel or mass; and that all velocity changes will occur instantaneously.

Findings and Conclusions

Conducting online research and interviews facilitated the development of the trade space of current SmallSat sensors capable of providing high-resolution imagery and onboard satellite imaging processing. High-resolution EO sensors compatible with SmallSats are commercially viable; Harris's SpaceView offers a variety of low cost high-resolution EO payloads. This sensor's staring mode, which provides sub-one-meter resolution at 525 km (Crawford, 2018), was used as the baseline imaging capability for this study.

We used Satellite Tool Kit (STK) software simulations to design the optimal constellation. The simulations use the satellite's access area to consider opportunities for imaging with the assumption that the satellite is tasked to point within the access area. The access area was restricted to provide no worse than one-meter resolution imagery. Simulation average revisit times ranged from 5 to 20 minutes depending on the constellation design, but there are gaps in access and maximum revisit (Crawford, 2018). These gaps can be predicted; however, to improve MDA utility, we designed a constellation that minimized their occurrence and duration. The simulations revealed that increasing the number of satellites within an orbital plane did not minimize the occurrence and duration of access gaps, but increasing the number of planes did accomplish this objective (Crawford, 2018). The optimum constellation, which minimizes frequency and gaps in excess of 60 minutes that occurred several times throughout the day, uses a triple Walker design of three different inclinations where each inclination has six planes and ten satellites in each plane at an altitude of 525 km; the total constellation consists of 180 satellites in 18 planes with a rough cost estimate of $2B (Crawford, 2018). The inclinations of the triple Walker vary from 17° to 34° because the best opportunity for revisit occurs when the orbital plane's inclination matches the latitude desired for coverage (Wertz, 2010). The triple Walker only provides coverage between latitudes 34° North and 34° South due to the selected inclinations and nature of orbital mechanics. While global coverage and an average revisit time of 22 minutes can be achieved with the 80-satellite, polar constellation, the resulting maximum revisit time on the order of two to three hours would not meet the desired MDA requirements (Crawford, 2018).

We researched various C3 methods, via online sources and interviews, and analyzed their ability to support a 180-satellite constellation in Low Earth Orbit (LEO). The constellation requires at least 480 kbps for data transfer, and we concluded that Mobile User Objective System (MUOS) or Inter-Satellite Links (ISLs), also known as crosslinks, are both potential options for continuous data relay (Begley, 2018). This data rate is calculated per satellite for 50 accesses at 9.6 kbps each, assuming that 50 satellites will be in view of each MUOS satellite (or three to four satellites per Wide Code Division Multiple Access (WCDMA) beam), which can provide a minimum data rate of 9.6 kbps. Based on the estimated image size of 400 KB, MUOS would be sufficient to support the minimum data rate required of 1.2 kbps per image. MUOS as a data relay system requires technology maturity; Space and Naval Warfare Systems Command (SPAWAR) is set to launch a CubeSat demonstrator of MUOS as a relay no earlier than July 2018 (Yoo & Mroczek, 2015). MUOS was also designed for a Doppler shift at aircraft speed, so development is underway by the MUOS program office to increase the design to the speed of a satellite, with implementation expected in 2019 (Begley, 2018). ISLs requires at least one ground station and adds complexity to the design of the satellite, which could require up to four additional pointing antennas. Viable command and control options include Naval Research Lab's Neptune Common Ground Architecture (CGA) or Harris Corporation's OS/COMET program (Begley, 2018). Neptune's primary ground station, Blossom Point Tracking Facility (BPTF) in Washington, D.C. requires few additional antennas to support the 180-satellite constellation and can provide ad-hoc tasking to satellites if there is an available communication path (Begley, 2018). OS/COMET has proven utility through use by Global

Positioning System (GPS) and Iridium; this system can provide more automation within the constellation and allow for a true network in space.

We found that one-meter resolution is required for processing software to determine not only the type but also the class of ship (Mcgowan, 2018). The technology exists for classification of imagery, but a complete automated processing solution for SmallSats does not. The Rapid Image Exploitation Resource (RAPIER) Ship Detection System (SDS) software owned by SPAWAR is the most promising for ship type classification (Mcgowan, 2018). An interview with a RAPIER SDS team representative, Mr. Bowes, highlighted its ability to process high-resolution satellite imagery and detection of up to 10,000 ships. While the software is ready for deployment at ground stations, it is only at Technical Readiness Level (TRL) 8 as a terrestrial system and is not ready for deployment onboard satellites (M. Bowes, personal communication, April 1, 2018). To increase the accuracy of classification, the RAPIER SDS team has identified that a processor using multiple machine learning algorithms is a critical component in having the capability of onboard processing to classify ships, which currently requires further development (Mcgowan, 2018).

Through the calculations performed for inclination and right ascension of the ascending node (RAAN) changes, we found that the most efficient launch campaign is to launch into an inclination of 17° at a given RAAN, then to conduct a burn to 25° inclination, followed by a second burn to 33° while maintaining the same RAAN. Finally, a RAAN change of 60° is conducted at the steepest inclination, with a deployment of the desired satellites at each new orbit. Consequently, we determined that both the Falcon 9 and Atlas V are capable of performing the desired inclination and RAAN changes. Initially, the Atlas V was the preferred launch platform; however, it would still require five launches (one launch would contain only two planes of satellites vice four) to deploy the constellation, and the Falcon 9 would require six. The total cost for the Atlas V is estimated to be around $545M while the Falcon 9 would only cost $372M, which essentially renders launch timing as the critical factor. In 2017, there were six Atlas V launches and eighteen Falcon 9 launches, indicating SpaceX has demonstrated the more robust launch tempo required for such a large constellation. While the Atlas V and Falcon 9 are the two primary considerations, there are a number of smaller launch companies focusing exclusively on SmallSats. Most notably, the Firefly β is capable of delivering 4,000 kg to 500 km at a cost of $15M per launch. The β is able to deliver 1.5 planes (15 180-kg satellites) to orbit, meaning it will require a total of 12 launches to deliver all 180 satellites. At $15M per launch, this totals $180M for the total constellation. However, the β is not considered a viable option at this time because it has only completed four launches so far and has not been proven as a reliable platform, nor does it have the operational support to perform 12 launches in a timely manner. Firefly β should be watched as its infrastructure develops further; as they begin to conduct routine launches, Firefly β could be the most cost effective means of deploying the desired constellation. With currently available technology and taking cost, the number of satellites per launch, and launch tempo into consideration, the Falcon 9 is the recommended platform to deploy this 180-satellite, Triple Walker constellation of SmallSats. Potentially, the entire constellation could be placed into orbit in six launches over the span of two to three months, costing roughly $372M.

Recommendations for Further Research

1. We recommend an investment in the following research:
2. Payload research for IR and SAR sensors.
3. Spacecraft design upon payload selection.
4. C3 for maintaining a responsive constellation to meet TCPED requirements for MDA needs.
5. Target recognition through the use of fully-automated AI processing.
6. Optimization analysis of the constellation to include different methods, such as street of coverage.
7. Detailed cost analysis to build, implement, and maintain the constellation.

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NPS-18-N300-A: Unclassified Maritime Domain Awareness (MDA)

Researcher(s): Dr. Dan Boger, CAPT Scot Miller USN Ret., Dr. Arkady Godin, Ms. Ann Gallenson, and Mr. Robert Schroeder

Student Participation: LT Kris Sousa USN, LT Dan Minter USN, Major Sam Ng SN, and CWO3 Vince Mosley USA

Project Summary

In 2015, a former Naval Postgraduate School (NPS) student postulated that emerging commercial satellite imagery, combined with computer vision (CV), might drastically change the nature of executing maritime domain awareness (MDA). He further surmised that this approach would deliver such detail and depth of data that the patterns of life (POL) for high priority vessels of interest (VOI) could be inferred, leading to predictive analytics.

In 2018 we completed our third and final year of MDA research based on the above premise. This paper explains the discoveries, operational implications, and challenges encountered in attempting to prove this hypothesis.

This effort included journeys near and far, explorations of many emerging technologies, and lessons learned with implications for longer term MDA. The hypothesis remained constant, always guiding the research whatever the branch we were chasing. Many students and researchers were involved. We found his hypothesis to be technically feasible, yet unachievable due to operational, resource, and organizational reasons. This executive summary explains the hypothesis in detail, a chronological review of the research achievements, and why technical hypothesis validation did not occur. We end with lessons, conclusions, and recommendations.

Keywords: *maritime domain awareness, computer vision, machine learning, non-cooperative vessels of interest, UN sanctioned vessels*

Background
MDA focuses effort related to growing awareness of maritime activity. The United States Navy (USN) prioritizes VOI based on strategic, operational, and tactical guidance. In the near term a VOI may be a warship of competitor countries, a United Nations (UN) sanctioned ship, or even illegal fishing boats, if any of these impact guidance.

Executing MDA, at its most basic, involves taking the steps necessary to develop an understanding of the five W's with respect to a VOI: What is the name of the vessel? Where is it, and where is it going? Why? Who owns and operates it? What are they carrying and for what purpose? When does it arrive? For most VOI, learning these items is easy. Vessels over a certain size are required to operate an Automatic Information System (AIS), which answers those five questions. Anyone can pay for commercial services that provide that information, or, like the Navy has done, acquire AIS receivers and generate the data themselves. Navy VOI are of interest for often criminal or other devious reasons where operating AIS is not in their best interest. Thus, most Navy VOI fake, spoof, or turn off their AIS.

Finding these kinds of VOI takes lots of intelligence work. It involves analysts leveraging snippets of information, resource-intensive collection plans, and tactical application of platforms such as ships, submarines, and maritime patrol aircraft. It may even involve national technical means if the priority is high enough. Finding a specific VOI can often be like finding a needle in a haystack, especially in well-traveled sea lanes.

Commercial images of the oceans are available, for a price. For this research we leveraged the products from Digital Globe, since the National Geospatial-Intelligence Agency (NGA) already pays for this imagery. There are many more sources, but resource constraints prevented us from accessing them. Since commercial imagery is geo-rectified and time stamped, one can surmise the direction, a rough speed (based on wake to hull ratio), location, and time from an image. The resolution is good enough to enable classification of ship types in broad categories, such as warship, tanker, container carrier, and fishing boat. But numerous challenges remain: image sizes are huge, and can take hours to download. Many images contain only cloud tops, which are not useful. Once the image is downloaded, it takes many more hours to spot ships, then explore and classify them. Our first set of students validated these difficulties.

CV can help resolve these issues. One feeds images of interest, usually VOI into a CV algorithm. Next, you collect images (in our case from commercial satellites, but these images could be from aircraft). The algorithm compares the new ones to the library of VOI, and alerts you to images which it thinks are the same. Especially early on, you "train" the algorithm by running lots of examples through the system, usually with human-provided feedback. While CV tantalizes as a time saving process, there are many new issues: Who supports the feedback loop? How does that loop work? What format does the image need to be in? Satellite images are from overhead, so will side views work? What if the VOI is partially obscured by clouds? Where does one get the original images for the VOI library?

We were fortunate to have CV support from the Office of Naval Research (ONR). They sponsor the Surveillance, Persistent Observation, and Target Recognition (SPOTR) project. SPOTR solved nearly all of the above issues. One key approach was that they use multiple images, from different points of view, to build an internal three dimensional model of the VOI, so that it is much easier for them to match images to the VOI library. This also enables them to classify any detection into one of eight categories, in accordance with the International Maritime Organization (IMO) standards. Because they applied this approach to many objects, they have validated their approach and know their false target rate, which is very low (actual number is sensitive information). They also automated the feedback loop and crowd sourced it, with remarkable and fast results.

SPOTR addressed the other issue of large file size by working with Digital Globe, Inc. (DG) to insert their algorithm directly at the DG ground receiving station site. Because the ocean is big and VOI small, the analyzed data sets are much smaller.

How does the Navy use this data? Each VOI is a different case, but in most cases the Navy tends to use the Observe, Orient, Decide, and Act (OODA) decision cycle. If SPOTR provides the observation, then what provides the orientations? In this research, the answer was SeaVision. SeaVision is an unclassified situation awareness display that displays mainly automatic identification system (AIS) and radar surface contacts. Since it uses multiple AIS sources, and correlates the duplicates, it is quite effective at tracking all the world's vessels, except for the VOI that spoof or turn off AIS (most Navy VOI), which the Navy sometimes calls "dark" targets. Part of the hypothesis was that by using the commercially available imagery supported with CV, we could deliver a third source of MDA information into SeaVision, and increase the ability of the Navy to orient their decision cycle of VOI. Since SeaVision is unclassified, it also meant that the Navy could share, if desired, VOI information with allied and coalition partners much more rapidly.

The initial piece of the hypothesis involved POL and predictive analytics. POL analysis is a non-trivial task involving detailed understanding of various VOI plus large sets of data points of VOI tracks. With enough commercial satellite imagery, and leveraging other sources of imagery, this is possible. However, again resource constraints prevented us from trying this. POL analysis also requires a specific data architecture. This was discussed and designed, but not built. Since predictive analytics are derived from POL development, we were unable to explore this in much detail. Still, the operational demand for predictive analytics exists, as highlighted in several requirements messages that we were privy to. Our research indicated that emerging technologies, such as those based on events, might shed new light on both POL analytics and prediction. There are other schools of thought that suggest that the causal relations needed to achieve these levels of analysis are not logical, and fail in their assumptions. This remains an area of active debate in the machine learning and artificial intelligence worlds.

Findings and Conclusions

The research remained primarily focused on executing the hypothesis with actual operational units and attempting to measure if the Navy's execution of MDA, especially against VOI, improved or was more efficient. We also explored related topics.

Researchers met with the 6th Fleet, 7th Fleet, and Joint Interagency Task Force-South (JIATF-S) MDA practitioners. All were interested in new ways to execute MDA; each had different needs. Since our operational research sponsor was the 7th Fleet, we focused on their area of responsibility, while enhancing our understanding with the other parties.

The 7th Fleet is very interested in one type of VOI, which they use other means to observe and orient on. While they were our sponsor, they were not interested so much in the hypothesis. They have a very short term time horizon. They directed us to Task Force 73/Commander, Logistics Group Western Pacific (CTF-73) in Singapore and their Southeast Asia Cooperation and Training (SEACAT) exercise. SEACAT is designed to explore MDA information sharing among Southeast Asia maritime partners. Though interested, they eventually dismissed our efforts as too forward-leaning for their partners to grasp and use. We attempted to use SEACAT anyway for VOI tracking, in the background of the exercise execution, but it became clear that this was too far down on the priority list for CTF-73.

This was exacerbated by a failure to have any MDA agency actually give us names of VOI. As stated above, the SPOTR algorithms compare incoming images to a library of VOI. Building that library is an important and difficult job. Images may be available from organic sources, but declassifying them is arduous. Many images (and even three dimensional models) are available commercially, but we faced resource constraints. The Office of Naval Intelligence has immense libraries of images, many unclassified, but it literally took an official letter from the Chief of Naval Research to the Chief of Naval Intelligence to gain access to these images. This occurred too late in our research to have value, though the SPOTR project team has been able to use them.

We also encountered difficulties in SPOTR and SeaVision collaboration, again due to resource constraints. SeaVision thought they would just ingest tracks derived by SPOTR. That was true, however SPOTR needed other tracks in return from SeaVision to validate their approach, which was misunderstood. Integration remains incomplete, but the SPOTR and SeaVision engineers have discussed how to proceed.

Student thesis work also focused on determining measures to ascertain the hypothesis results. Given a set of VOI, the students investigated how to establish a baseline for current VOI MDA. This can be accomplished by leveraging current SeaVision data. Again, the team ran into issues. While SeaVision has data back several years, they only enable user access back 90 days. While useful in many ways, establishing a good baseline would need more data than was available to the students.

The students suggested what the baseline might look like. That is, for any given VOI, how often was it at sea? Were there inconsistent track data or suspicious gaps of track information? The idea was to then compare the VOI data when the SPOTR to SeaVision connection was made. We believed that over time, and with increasing image sources, that the periods of time where VOI were unaccounted for would decrease. This means that tactical resources currently tasked to find and track VOI might be better used on other missions.

The hypothesis focused on unclassified efforts. Information sharing of classified information to allied and coalition partners is time consuming, and thus not tactically relevant, since by the time information is finally passed, it is too late to take action. Thus the hypothesis was focused on the unclassified nature. Regular naval operations are usually conducted at the SECRET level, so the hypothesis was often discounted by U.S .Navy operators as not needed. However, in many private conversation with operators, most had stories on how they could have reacted much faster in their OODA loop if they would have been able to share faster. This is even more important, since the U.S. Navy has fewer ships, and is making many efforts to operate as a combined force with allies and partners.

A special case is JIATF-S, which operates as a multinational task force. They work diligently at information sharing, trying their hardest to keep it unclassified. The research finding was that the level of effort to maintain information sharing requires a dedicated culture shift and never-ending pressure to continue sharing. The default, it appears, is to not share.

Three spinoffs of the research are noteworthy. Early in the research, we met other NPS researchers involved with social network analysis of MDA related data. They needed VOI to serve as the object to concentrate their analysis on. They saw our process as a way to detect and identify “dark” targets. We collaborated with this team, and the last set of students are writing a thesis on how to integrate the two capabilities. While successful, their sponsors focused on a different geographic area, so complete integration could not be achieved. Also, they lost a year of research to resource constraints. We believe their analytical approach might also help answer the “What” questions, and might be useful in the POL acquisition.

The second spin off was very successful. While at 7th Fleet, the imagery analysts there wondered if SPOTR could help them with an image-related issue. They check images of various ports of interest daily, seeking to understand changes. Since this was vessel related, SPOTR thought they could detect if any given image of the same place had experienced changes, at least with respect to vessels. After three months this capability was operational at 7th Fleet, and has now been expanded to the 5th Fleet and the 24th Intelligence Squadron at Ramstein AB (where the change detection is executed on more than just vessels).

The third spinoff was recognition that SPOTR works on images taken from any camera. Thesis research was conducted to explore the concept that every air vehicle in the naval inventory ought to use SPOTR to detect various intelligence and operational objects of interest. SPOTR had already proven this in two experiments. The thesis was passed to the Marine Corps and the Naval Aviation Systems Command. The Maritime Patrol and Reconnaissance Force Weapons School was also briefed.

Recommendations for Future Research

Technically, the hypothesis will work. There are integration issues, but none noteworthy. To achieve POL and predictive analysis requires a sufficient data architecture to support additional artificial intelligence tools. The data architecture requires paying attention to the five V's: volume, veracity, value, variety, and volume, since failure to account for them would result in slow or inoperable functionality. Since POL is difficult, the additional algorithms required may require significant investment.

CV is a machine learning (ML) based approach. POL would likely use similar ML or artificial intelligence approaches. These are most successful with lots of data. DG imagery is not enough input to meet those ML data requirements. Successful implementation of this approach would require subscription to other commercial satellite resources at additional cost.

While the research team believes that this approach would result in more effective dark MDA VOI tracking, and also provide a more efficient use of resources, actual metrics, as described above, need to be collected. There is also the potential issue of the compilation of many unclassified sources that, when combined, might produce information that is regarded as classified. More work is needed in this area.

Another area of further research is recommended. If researchers from NPS can put together a capability with little resources to detect almost any known vessel at sea using just unclassified and readily available data, what repercussions does this have for the Navy in their operations? In theory, a competitor with resources could use the same techniques focused on vessels of their interest, e.g., U.S. Navy vessels.

The research team almost received a key breakthrough in April 2018, when 7th Fleet indicated that UN sanctioned VOI were of particular interest. The team was confident that this approach, combined with the dark MDA networks research, could bear immediate operational fruit. No follow up occurred by 7th Fleet.

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NPS-18-N382-A: Satellite Planning Models

Researcher(s): Dr. Luqi, Mr. James Horning, Mr. David Rigmaiden, and Dr. Wenschel Lan
Student Participation: Maj Chris Wildt USMC

Project Summary

Naval forces need prior knowledge of overflight by satellites for effective planning. This includes positions of friendly satellites that are expected to provide intelligence, surveillance, and reconnaissance (ISR) and communications support to our forces as well as positions of adversary and commercial satellites that could potentially detect and report planned Navy activities via various onboard sensors.

We identified differences between the Simplified General Perturbations model 4 (SGP4) United States Air Force (USAF) and Position and Partials as a function of Time v3 (PPT3) United States Navy (USN) orbit propagation models, and determined their impact on positional error in orbit determination. PPT3 and SGP4 both perform well within the expected accuracy limits inherent in analytical models, with neither propagator demonstrating an accuracy rate decay that was significantly better or worse than the other.

The two-line element (TLE) format is under change now, the new TLE and three-line element (3LE) formats are still under review, data in the new format is not being distributed, and the current version of SGP4 does not support the new formats. The new formats are to add additional types of information about the satellites, many not related to their orbits. Information in the new third line related to primary payload mission, primary mission status, and payload owner/operator provides context for satellite vulnerability planning, and is relevant for deciding which satellites should be monitored closely and choosing update rates for TLEs and 3LEs.

Keywords: *Naval Ship Vulnerability, Satellite Overflight Prediction, Accuracy Assessment, SGP4, PPT3*

Background

The purpose of the research is to assess the difference between the two models of orbit propagation that are currently in use (SGP4 and PPT3). Specific research objectives were:

1. Assess which model characteristics are most significant for satellite planning systems.
2. Compare the relevant aspects of legacy models and the newer models.

The classical textbook solutions that yield elliptical orbits assume that gravity comes from a single point mass and that there are no other forces acting on the satellite. The real situation is different: motion of near-earth satellites is affected by (1) drag from the thin vestiges of the atmosphere at their altitude, (2) deviations from the point mass approximation because the earth is not perfectly spherical and the distribution of mass in the earth is not perfectly uniform, (3) other sources of gravity, (4) light pressure, (5) the solar wind, and so on. While all of these effects are much smaller than that of the earth's gravity approximated as a point mass, over time they build up to produce deviations from the stable elliptical trajectory described by the textbook solution to the simplified orbital problem.

Astrodynamics was a quiet scientific endeavor of little national import until October 4, 1957 when the Union of Soviet Socialist Republics (USSR) launched *Sputnik-1*, the first artificial Earth satellite. On November 29 of the same year, the Air Force established Project Space Track to track and compute orbits for all artificial Earth satellites, including U.S. and Soviet payloads, booster rockets, and debris. On March 17, 1958, the U.S. launched *Vanguard 1*. Then Dirk Brouwer and Yoshihide Kozai wrote their articles on artificial satellites in November 1959 (Brouwer, 1959 and Kozai, 1959). They utilized spherical harmonics for Earth's non-uniform gravity field, and their work laid the foundation for today's orbital prediction theory.

To translate the theory into a working computer model, other research had to be incorporated. The usage of R. H. Lyddane's solution to small e and I divisors (Lyddane, 1963) and the King-Hele atmospheric model allowed Brouwer to develop the PPT model. It ran on the IBM 7090 computer at Dahlgren, VA, was the largest available in 1964. Brouwer and Kozai would later collaborate on the SGP4 model, which included fewer zonal harmonic terms and used a simple atmospheric model, though this was changed to a more complex model in 1969. It remains the Air Force's primary tracking system.

PPT3 and SGP4 use different simplified models of atmospheric drag. PPT3 is a simplified version of PPT that drops some of the less significant parts to speed up the computation. This was necessary to make the computations practical on computers available when the models were developed. Initially the computations took 15 minutes per satellite (Hoots, Schumacher, & Glover, 2004). They are much faster now due to better hardware. The benchmark for Naval Postgraduate School Satellite 1 (NPSAT1), a small spacecraft built at NPS that uses an ARM LH79520 (a 32-bit ARM7TDMI core) that runs at 51 MHz (no floating point hardware), does one iteration of SGP4 in just under 5 msec. Processor cores in most current laptop computers are about 50 times faster than that. This implies that processor speed is not a limiting factor for the models any more, and that it should now be feasible to use the full PPT model if needed.

Findings and Conclusions

Material was gathered and analyzed on the larger context for this inquiry, such as publications and the Navy context regarding motivations for accurate satellite tracking and prediction. Results were reported to more than three dozen interested people from the DCNO for Information Warfare (N2/N6), the DCNO for Operations, Plans and Strategy (N3/N5), Director, Fiscal Management

Division (N82), Director, Innovation, Test and Evaluation, and Technology Requirements (N84), DCNO for Warfare Systems, Director for Undersea Warfare (N97), Naval Information Forces (NAVIFOR), Space and Naval Warfare Systems Command (SPAWAR), and NPS in a summary teleconference on June 22, 2017. A master's student was extensively involved in this study, resulting in a master's thesis (Wildt, 2017) and a conference publication (Lan, 2018). The two analytic models studied, SGP4 and PPT3, are not the most accurate ones currently available, but they require significantly less computation than the more accurate numerical models, resulting in faster response times. Both of the models need to be frequently recalibrated using least squares fits to measured satellite position data, and the accuracy of both SGP4 and PPT3 is good enough for satellite vulnerability (SATVUL) planning if that is done. The extra accuracy of the numerical models is needed in other contexts such as satellite maneuvering, rendezvous operations, etc.

Differences between the models were validated and assessed by comparing model predictions to real-world satellite measurements, with the following findings:

- Both propagators calculate drag within analytical expectations (1-3 km per day margin)
- Neither has a significantly better error rate than the other
- Accurate input data is needed to get good predictions
- Imperfections in the TLE data were observed, along with effects on model predictions
    - In particular, the B*(best-first graph search algorithm) component was incorrectly set to zero in multiple TLEs
    - This affected SGP4 but not PPT3, whose drag model does not use B*
- Accuracy increases outside of the atmosphere for both models
- For satellite vulnerability planning:
    - Timeliness of orbit element [TLE] input is important!
    - Altitude of the satellite should be considered before extending predictions 3+ days past epoch – the errors accumulate faster for satellites in lower orbits.
    - Build time buffers into SATVUL plans, for immunity to accuracy errors

The errors for both SGP4 and PPT3 were found to be within the expected range of 1km $\pm$ 3km/day. We believe the accuracy of both models is good enough for Navy satellite vulnerability planning if the orbital elements driving the models are updated frequently enough, for the following reasons:

- Procedures for stowing sensitive equipment, turning off radiating signals, or concealing local presence will take time on the order of minutes, not less than a second, and that satellite vulnerability planning scenarios will include enough extra lead time to ensure that detection by satellites is avoided despite expected variations in predicted overflight times.
- Typical speeds of satellites in low earth orbit are about 7.5 km/sec. An expected 4 km error in predicted position therefore corresponds to an overflight time error of 4/7.5 sec = 0.53 seconds, which would not be significant under the above assumptions.
    - The expected error in this scenario corresponds to TLE updates once per day.
    - Solar storms can change the atmospheric density, increasing expected prediction errors for both models. TLEs should be updated more frequently during periods of increased solar activity to compensate for this effect.

Since there are web tools for updating satellite orbital elements, they can be updated frequently, and training for every Strike Group Communication Officer and N6 emphasizes this prior to deployment.

Factors other than accuracy of orbit predictions also affect SATVUL planning. Satellite vulnerability windows depend on the position of the ship, as well as the position of the satellite and the field of view of its instruments. The actual positions of Navy ships can deviate substantially from their planned position of intended movement (PIM) due to emergent operational needs and other unpredictable disturbances. For this reason, it is recommended to calculate satellite vulnerability windows in real time on board ships in a battle group, using orbit model parameters disseminated from satellite tracking centers. This concept of operation (CONOP) should be more effective than centralized calculation and dissemination of the SATVUL predictions. Local SATVUL processing would enable accurate real-time ship positions to be used in the calculations, as measured on board the ship, instead of relying on the ship's planned PIM. This should lead to more accurate satellite vulnerability window predictions.

Since error of predicted satellite prediction increases with time since the last measured position of the satellite, it is also recommended to disseminate real-time updates of model parameters to ships for automatic update whenever there is bandwidth in the communications system that is not needed for higher priority information. This would remove risk due to possible delayed human action, because the people currently responsible for updates are likely to have more pressing concerns during crises.

Since the accuracy of both models improves for higher orbits, it is recommended that the priority for orbit parameter updates consider orbit altitude in addition to risk factors associated with the satellite, with more frequent updates for lower orbits. Frequent TLE updates would also reduce exposure to prediction errors caused by changes to satellite configuration, such as navigational maneuvers and modifications to a satellite's shape and orientation that affect its drag coefficient.

Recommendations for Further Research

Additional research and development are recommended with the following objectives:

- Engagement with Air Force Space Command (AFSPC) to acquire full PPT3 and model calibration codes, make comparison of more satellites possible, and enable thorough validation and assessment.
- Gain full understanding of PPT3 initialization, to enable development of a more usable and portable application programming interface.
- Additional analysis of the variation/errors seen in TLE data, to enable assessment of data feed quality. Predictions are no better than the data they are based on, and our initial study found data with unexpected values (Wildt, 2017).
- Additional analysis of variation/errors seen in 3LE and 4LE data and prediction improvements enabled by that data.
- Development of full data models for orbit data that completely specify the meaning of the data, in addition to its format. The additional information needed includes measurement units, coordinate system origin and orientation, and conventions for defining all the orbit parameters, with emphasis on details of the ones that are interpreted differently in the two main propagation models, such as mean motion and semi major axis.
- Alternatively, develop a full data model for the de facto TLE standard matching SGP4, and transform the front end of the PPT3 implementation to read an SGP4-dialect TLE and internally convert it to the form needed by the PPT3 algorithm, to prevent confusion between different variants of TLE data.
- Since computers are much faster now than in the 1960's, consider implementing the full PPT model. PPT3 dropped some of the terms in PPT to speed up the computation as needed then to keep up with the TLE update rate, introducing some loss of accuracy. PPT should provide better accuracy than PPT3 while keeping the computation time less than that of more accurate numerical orbit prediction models, which estimate satellite positions and velocities at many intermediate points in time and hence require more computation for orbit prediction than analytical models such as SGP4, PPT3 and PPT.
- Revise I/O routines to accommodate the new TLE/3LE formats, revise the SGP4 and PPT3 models to fully the new information in them, and start distributing data in the new formats.

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N3/N5 - PLANS & STRATEGY

NPS-18-N074-A: Improving the Special Operations Lessons Learned Program (SO LLP)

Researcher(s): Dr. Shelley Gallup, and Dr. Erik Jansen
Student Participation: No students participated in this research project.

Project Summary

Lessons learned programs have been less than fully useful at most military organizations. This project looked specifically at the Lessons Learned Program (LLP) at the Naval Special Warfare Command (NSWC). The intention for the research was to analyze the LLP as a system within the context of the NSWC organization using the Congruence method for organization performance and fit. This framework provides an open-systems model in which all elements of a dynamic organization can be understood as connections to other elements of the organization. Formal documentation that sets policies and procedures for the NSWC were analyzed according to each of the elements of the Congruence framework, and recommendations for improvement in key areas were provided. This is a two-year project, with this next year looking at the specific needs for improvement, and the means for implementation. These means can be policy changes, specific training, organizational changes, improved technology for knowledge distribution, and knowledge conservation using big data/machine learning techniques.

Keywords: lessons learned, knowledge management, organizational fit, big data, machine learning.

Background

Knowledge can be conserved and if made available for re-use can provide potential competitive advantage in military and industry organizations. Use of expert systems approaches is an example, and particularly useful in capturing nuances of human actions in routine activities. The military has many such routines, but in shifting contexts and potential warfare on a global scale, these routines are not effective in meeting the variety of the environment. In his March, 2001 thesis, Garvey wrote:

"The Navy Lessons Learned System (NLLS) was formally created in 1991 by CNO direction as a result of a growing fleet interest in providing a centrally managed and easily accessible lessons learned database. In 1995, a congressionally ordered Government Accountability Office (GAO) report was released that was critical of all the services and their potential to use lessons learned as a means to avoid repetition of past mistakes. Consequently, the Chief of Naval Operations improved on this system by instituting and formalizing guidance in the form of an Office of the Chief of Naval Operations (OPNAV) instruction. Its purpose was to standardize and delineate the NLLS requirement and formal feedback process. The Navy Lessons Learned System that developed was patterned after the Joint Chiefs of Staff (JCS) sponsored Joint Universal Lessons Learned System (JULLS). This system currently makes up the formal feedback process." (Garvey, 2001)

Although mandated many organizations created their own versions of lessons learned programs, and organizationally there were difficulties implementing what was needed.

Findings and Conclusions

Although this is the completion of one year of a two-year study, some results have surfaced for further study in the next year's effort. These results are the result of discussions with the owners/implementers of the NSWC Lessons Learned Program, cross organization review of the different policy documents, user training, and technology for implementation.

Specific issues included:

- Lack of cohesiveness and fit between the policy documents that frame the Navy's lesson learned system at large, and the specific operationalized version of the LLP at the NSWC.
- Lack of access by personnel at different levels and specialties across the organization.
- Cross domain issues that prevent sharing of knowledge with teams that are forward deployed or on operations.
- Technology (SharePoint) that is no longer supported by the contracted developer.
- Knowledge Management and LLP are generally two different organizations throughout the NSWC, often manned by different contracting organizations.
- Differing views of LLP utility depending on organizational roles (the NSWC is composed of differing specialties, each with their own needs).

When placed into the Congruence framework, these issues can be seen to contribute to a lack of overall fitness, and provide a useful place from which to advance possible prescriptions for improvement.

Recommendations for Further Research

As noted above, there is a second year of this project. The issues listed here are the most significant found to date, but others may arise in continued analysis. For each issue, a different prescription for change and implementation will be offered. A second round of organizational fit will then be conducted to determine that the prescription is technically, organizationally, and fiscally feasible.

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NPS-18-N077-A: Hiding In Plain Sight: Logistics in WestPac

Researcher(s): Dr. Wayne Porter, CAPT USN Ret., Dr. Kenneth Doerr, and Dr. Emily Craparo
Student Participation: LT Laura Baumgartner USN, and LCDR Jonathan Krenz USN

Project Summary

This study was undertaken to assist Commander Logistics Force Western Pacific in understanding vulnerabilities in a supply chain that includes United States Naval Ship (USNS) ships, United States Navy (USN) ships, operating companies, civilian military unions, and a large contracting footprint in order to minimize operational risk to mission and optimize logistics resources and operations, while maintaining command and control (C2) of operational forces. The study included Red Teaming of current practices, *distributed logistics*, and *optimized routing*; *supply chain management* and the impact of *reliability*, *availability*, and *maintainability* on readiness; and social network analysis of the *maritime logistics network* in Western Pacific (WestPac) and a *social media vulnerability assessment*. An assessment was made of *logistics risks* associated with surge/peak demand at a single facility, and a prototype module was developed, as a proof-of-concept. This tool can be used to perform what-if analysis, in the evaluation of policy changes related to technology purchases, *pre-positioning plans*, or outsourcing decisions. The research constructed a *discrete-time optimization model* and used this model to analyze a variety of finite-duration operational scenarios. The model was also used to perform *sensitivity analysis* on various parameters of ship design, including amount of storage space for palletized cargo and the breakdown of the liquid capacity need for each type of fuel (JP5 and DFM). Sociograms were produced to depict the *maritime logistics network* and a separate assessment of *social media vulnerabilities* was provided. An *interactive tool* was developed to allow Task Force 73/Commander, Logistics Group Western Pacific (CTF-73) to further analyze aspects of the logistics network to include ships, ports, and loitering areas.

Keywords: *distributed logistics, optimized routing*, *supply chain management, reliability*, *availability*, *maintainability, vulnerability assessment, logistics risks, pre-positioning plans*, *discrete-time optimization model, sensitivity analysis, maritime logistics network, social media vulnerabilities, interactive tool*

Background

The U.S. Navy's at sea replenishment system is a mobile supply line designed to support the deployed Carrier Task Force (CTF)/Cruiser/Destroyer (CRUDES) Surface Action Group (SAG) and forward deployed units while at sea. In the 7th Fleet area of responsibility the main component of the mobile supply line, the Combat Logistics Force (CLF) ship, has become a possible target with the development of the anti-ship ballistic missile (ASBM). With the ability to target and disable a CLF with an ASBM, an enemy can now disable a deployed CTF/CRUDES fleet by eliminating its required replenished resources, rendering it combat ineffective and more vulnerable to attack. With the goal of preserving the CLF's capabilities to perform its mission while not subjecting it to an ASBM threat, we consider the possibility of utilizing a "mini-CLF" to shuttle fuel and other commodities between CLFs operating in a safe environment and warships operating in a threat zone. Metrics to assess logistics risks are a pillar of supply chain surety: the assessment of risk to assure performance, not merely control and mitigate points of failure. Logistics risks are multi-faceted and interdependent; all relevant facets of logistics risk must be measured, or one might unintentionally increase one risk while mitigating another. Logistics risk includes readiness risk (risk to operational availability), as well as capacity risk, supply risk, schedule risk, and budget risk; all these risks are interdependent. The application of social network analysis and open source data base integration for the identification, mapping and tracking of vessels, owners/operators, facilities, activities and cargoes has been successfully employed by the Naval Postgraduate School (NPS) in a previous Navy-funded research project. A unique aspect of this research, is that social network matrices can be dynamically updated by open-source data bases to provide real-time awareness and tracking for operational purposes. Further, extensive social media exploitation research has been done in the NPS Common Operational Research Environment (CORE) Lab to better understand areas of potential operational security (OPSEC) vulnerability, and interactive tools were developed and tailored for the sponsor.

Findings and Conclusions

Operations Research

We obtain a number of insights from our four scenarios that considered three strategic situations: Peacetime, Rising Tensions, and Wartime. The first two scenarios demonstrate an important aspect of the rolling horizon optimization framework. Although we have more resources available in the second scenario, theoretically allowing better solutions, we observe that decisions made in early iterations of the rolling horizon sequence can result in inferior solutions in subsequent iterations. This important phenomenon should not go unnoticed by practitioners considering a rolling horizon approach.

We also note that in a rolling horizon framework, it is important to choose a long enough planning horizon to model any decisions we would like the model to be capable of making. With this in mind, and given that it would take a CLF ship up to 56 time periods to move from an Aft RAS Lane (ARL) to Guam and back, we extend the planning horizon from 60 time periods to 90 time periods in the third excursion. Although a 60-period horizon would have allowed the movement to take place, the model would not have seen any benefit from making this decision. We also change the shuttle and CLF starting inventories to reflect them having been operating at sea for some time. After making these changes we examine Scenario 3. From these results we observe that a primary limitation is the number of fleet replenishment ships (T-AOs) in the scenario. Prior to the last 30 time periods, the warships' Diesel Fuel Marine (DFM) inventories only fall below the safety level for a few time periods and by a small amount (1-2%). Had a second T-AO arrived between time periods 47 and 90, the shuttles would have been able to maintain the warships' DFM inventory levels. These results also show that the dry cargo/ammunition ship (T-AKE) is ill-suited for supporting this type of operation. The T-AKE has large quantities of stores and ammunition but smaller quantities of DFM and JP5. A fast combat support ship (T-AOE) could be a better support vessel for this type of operation as it brings comparable quantities of stores and ammunition as the T-AKE, but an additional 71,000 barrels (bbls) of DFM and 61,000 bbls of JP5 (CNO, 2007).

It is also interesting to compare our first and fourth scenarios. Both involve a Rising Tensions strategic situation, but the fourth involves more shuttles traveling at faster speeds, and it uses a longer planning horizon as well as an 80% starting inventory (vice 100% for the first scenario). Interestingly, in the fourth scenario, the warships spend more time below the safety level for DFM and jet engine grade fuel (JP5). We speculate that this is due in part to the combination of a lower starting inventory and more shuttle ships. Ostensibly, more shuttles should result in better performance. But it is important to remember that while shuttles are delivering fuel, they are also burning it. When we reduce the starting inventory of the shuttles and CLF ships from 100% to 80% and increase the number of shuttles from four to six, we reduce the starting amount of deliverable DFM from 195,000 bbls to 191,200 bbls and the starting amount of deliverable JP5 from 100,400 bbls to 81,680 bbls. At the same time, we increase the usage rate of the system by 320 bbls of DFM per time period and 3.40 bbls of JP5 per time period. This decrease in starting inventory levels and increase in usage per time period reduces the effectiveness of the system, and this reduction is not completely mitigated by the increase in speed and number of shuttles.

We confirm that Dual Lane Replenishment at Sea model (MC-DL-RASM) produces reasonable results in the four scenarios we examined, and that the "mini-CLF" concept of operations is a viable alternative to the traditional CLF concept. We observe that the rolling horizon approach works best with a planning horizon of at least 79 time periods due to the length of time it would take a CLF ship to make the trip from ARL 3 to Guam and back to ARL 3 (54 time periods), then fill up a shuttle (2 time periods), and have it transit to forward RAS lane (FRL) 7 (22 time periods) and resupply a warship (1 time period per warship). In fact, even this horizon is a bit optimistic when we take into account the fact that RAS events can only occur during daylight time periods. We also observe that in each scenario, the shuttles will RAS with the CLF ships if possible rather than using a port to resupply. This could be an indication that having a port available in the area of responsibility (AOR) is not as important to maintaining the warships on station as having a constant supply of CLF ships.

Combat Logistics

This paper has reviewed several risk metrics and made recommendations. Quantile risk metrics such as value at risk (VaR) have been recommended as a way to track and control logistics risk. Conditional value at risk (CVaR) has been recommended as a way to assess the value of surety investments. Commonly used metrics such as standard deviation, coefficient of variation (CoV) and ordinal (color coded) risk metrics have been shown to have significant shortcomings. Reference has been made to ways of estimating risk from data, and calibrating the subjective estimates of subject matter experts, and using Bayesian Updating to improve such estimates as data become available. Military Sealift Command (MCS) has been presented as a way to build predictive risk models that can tie logistics processes and expenditures to mission outcomes. Some of these metrics have been demonstrated on the 688 Class Submarine Dry-docking Selected Restricted Availability (DSRA) process on a small dataset, and recommendations were made on which sub-processes might be explored, and what additional data might be required to reduce schedule and budget risk, and improve its prediction. Those results are not included in this summary because they are unclassified For Official Use Only (FOUO), but they have been delivered to the sponsor.

Risk management is a complex topic, complicated by with varying degrees of risk acceptance. This is regrettable because the subsequent (over) reaction may make it more difficult to promulgate some very useful tools. The useful tools for risk management are not new at all, though refinements continue to be made in risk management, as in every field. What is new is the attention being devoted to risk, caused by e.g., the financial crisis of 2007-2009, and the more recent wave of institutionalized, and “weaponized” cyber-crime that has exposed network vulnerabilities. Unfortunately, great attention (and large amounts of money being spent) causes a need for action that sometimes outstrips expertise, or even common sense. What is new and useful (at least in some organizations) is the availability of large amounts of data with a relatively high integrity, which can be used in risk management applications. However, some risk management, in the Department of Defense (DoD) and elsewhere, continues to be done with inappropriate tools, and with little or no relevant data.

It is important to measure risk appropriately in order to verifiably reduce that risk through training, and other investments in reliability. Where it cannot be reduced, risk must be quantified so that an acceptable level of risk can be buffered against in a cost-effective way, via safety stocks and surge capacity. When buffers are exceeded, risk must be quantified so that contingency plans can be resourced to restore normal operations as soon as possible. Buffers and contingency plans for logistics surety require scarce funds that can be used for other priorities across the enterprise.

So, finally, logistics risk must be tied to readiness and mission risk, to facilitate an appropriate allocation of funds among activities that compete to provide mission capacity.

In the consideration of future major war scenarios, the salience of budgets for readiness reaches new levels of importance. In the Civil War, the First World War, and World War II, the United States was willing to shoulder a mountain of debt to meet wartime challenges. Now, the U.S. is already shouldering a mountain of debt, without a major war. Inexorably over time, more debt means more expensive debt. If we enter a major war with this level of debt, even if we win, a doubling of our current level of debt may cause permanent damage to our status as a world power.

Defense Analysis/CORE Lab

Maritime Network Analysis: The behavior for ships from both the Maritime Sealift Command and the Maritime Security Program Fleet (MSP) were analyzed in order to identify patterns in the shipping logistics network. These patterns of shipping behavior could indicate how centralized (or decentralized) the shipping logistics network is as a whole and which locations in the United States Indo-Pacific Command (USINDOPACOM) AOR are most important to the logistics network. This report analyzes the USINDOPACOM shipping logistics network to help identify which areas are central to the network as a whole, and which subsets of ships (in their associated operations areas (OPAREAs)) are central to different portions of the network.

What becomes clear from this analysis is that there is a high degree of predictability associated with the CTF-73 logistics network as a result of overdependence on the primary ports of transshipment. This creates vulnerabilities to disruption during times of crisis or conflict. By distributing transshipment ports more widely among partner or friendly nations, there would be a greater likelihood of survivability/sustainability of the logistics network as a whole.

Social Media Exploitation: An initial edge list (a matrix of social media nodes) was gathered by looking for accounts on Twitter that mentioned ships of interest in their tweets within the last year. This search yielded a total of 386 Twitter account handles of interest. This initial list of accounts was used as a springboard for exploring the online network. In an effort to identify the important accounts from this directed (connections that are unidirectional) network, we ran hub (highly connected nodes) and authority (key repositories of specialized information to which hubs are pointing) score algorithms.

The key take-away in terms of social media vulnerability, is that nodes with high hub and authority scores are most vulnerable to exploitation as sources of information regarding the CTF-73 logistics network. It would be useful for official Navy sites to monitor the type of information that is being publicly shared and those sites that routinely follow these accounts. Further, local media reporting of CTF-73 activities should also be routinely monitored and assessed.

Recommendations for Further Research
Future research could consider heuristic approaches to planning, as an alternative to integer programming. We have given examples of how logistics risk can be tied to readiness risk and mission risk through simulation. Given the budget constraints we face, we recommend that further research explore simulation models, to assist in the proper allocation of scarce budgets to those logistics processes that contribute most to the reduction is readiness risk and mission risk. Future research might also want to apply the maritime network analysis tools we have developed and tie this analysis to optimization and risk models we have discussed. Social media exploitation research might also delve more deeply into a variety of social media sources to further identify potential OPSEC vulnerabilities within the logistics network.

NPS-18-N251-A: Limited Nuclear Conflict

Researcher(s): Dr. Mikhail Tsypkin, Dr. David Yost, Dr. Christopher Twomey, and Dr. Donald Abenheim
Student Participation: No students participated in this research project.

Project Summary
This project examined limited nuclear conflict and escalation control in the policies of Russia and NATO. Russia has repeatedly reformulated its military doctrine in conjunction with ambitious nuclear force modernization and the pursuit of advanced non-nuclear capabilities. While the 29 NATO Allies have agreed policies regarding nuclear deterrence, ultimate control over nuclear weapons in the Alliance resides with Britain, France, and the United States.

Since the year 2000, three iterations of the Russian military doctrine have contained clauses permitting Russia to use nuclear arms against an enemy that might, using conventional capabilities alone, put the Russian state at the verge of collapse. The Russian plans for nuclear first use have focused on using non-strategic nuclear weapons (NSNW) for escalation: beginning with threats, then moving on to single demonstration strikes, and gradually up to massive attacks against enemy forces in the theater of military operations.

The NATO Allies have for many years expressed interest in escalation control and restoring deterrence in the event of conflict, notably in the 1967 MC 14/3 "flexible response" strategy. After the end of the Cold War in 1989-1991 the Allies neglected escalation control. However, Russia's actions, notably in Georgia in 2008 and Ukraine in 2014, have led the Allies to reconsider the challenges of escalation control.

Keywords: *Russia, nuclear weapons, NATO, deterrence, escalation control, limited nuclear conflict*

Background

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

Russian military planners have regarded nuclear first use threats as a necessary compensation for the weakness of Russian conventional forces since the collapse of the Soviet Union. Russian policies concerning the situations for — and timing of — crossing the nuclear threshold have remained undisclosed in order to keep the enemy off balance. The Russians appear to assume that the threat of nuclear use (or actual limited use of NSNW) would convince their opponents to cease or at least to de-escalate hostilities, because the cost of continuing combat would be greater than the foreseeable benefits.

At the same time, the Russians drew lessons from the U.S. campaigns in the Balkans and the Middle East, and carefully read the U.S. Nuclear Posture Reviews since 2001. Their conclusion was that long-range non-nuclear precision strike weapons could become the foundation for Russia's non-nuclear regional strategic deterrence. In the Russian view, the destructive power of these weapons would approach that of very low yield nuclear weapons, but their use would be less likely to provoke nuclear retaliation. The relatively large-scale use by the Russian military of long-range non-nuclear precision strike weapons during the campaign in Syria has convinced the Russians that they are on the right track with their plans to eventually shift a number of missions from nuclear weapons to non-nuclear ones. A key question is when (and if) Russia's economy will allow it to acquire a large number of such weapons and corresponding intelligence support systems.

For NATO, in the event of Russian aggression, the aims would be to stop Moscow from going to higher levels of destructiveness or to new domains of operations — geographical or functional — and to negotiate an end to the fighting. The Alliance's immediate political goal would be to restore the security and integrity of the NATO area. If prompt war-termination was infeasible, an interim form of escalation control might be obtainable: intra-war deterrence — that is, successful containment of the combat operations underway within certain geographical or functional domains, pending an end to combat and the restoration of the security and integrity of Alliance territory.

Significant unknowns regarding Russian policy on escalation control persist. Russian efforts to deter and intimidate NATO nations are obvious, and this makes the prospect of Russian efforts to coerce NATO Allies in a crisis plausible. Some Russian escalation boundaries are probable, despite long-standing Russian assertions that nuclear escalation is uncontrollable.

Since 1974 the Allies have recognized the distinct roles of Britain, France, and the United States in the Alliance's nuclear deterrence posture. The Allies regard the engagement of these three countries in the Alliance's Enhanced Forward Presence deployment as highly significant and positive for deterrence.

Findings and Conclusions

Russia may eventually drop the clause on nuclear first use, but this will not matter as long as it maintains its arsenal of NSNW capable of striking targets throughout Europe and the relations between Russia and its European neighbors are tense. Even if Russia tomorrow removed the nuclear first use language from its military doctrine, the years of threats would outweigh any verbal assurances. Europe has in certain respects returned to the nuclear standoff of the mid-1980s.

Threats to the NATO Allies below the threshold of Article 5, the mutual defense pledge in the North Atlantic Treaty, have emerged — including cyber-attacks, information operations, economic and energy coercion, and chemical attacks such as the Novichok operation in Salisbury in March 2018. NATO has therefore been assessing the organization of appropriate responses for escalation control below the level of Article 5. U.S. political leadership in crisis management and escalation control will remain imperative. The new challenges for escalation control include cyber, space, and thermobaric capabilities as well as long-standing messaging and signaling challenges.

Recommendations for Further Research

Future researchers should examine the full range of issues associated with escalation control in a limited nuclear conflict, including the maintenance of alliance cohesion and communicating NATO's intentions in a confrontation. Because Russian miscalculations could present risks of conflict, it is essential for the NATO Allies to develop a more nuanced understanding of how the Russians view their instruments of influence, intimidation, coercion, and combat. As in the past, Russian concepts such as "de-escalation" and "strategic non-nuclear deterrence" deserve monitoring and careful analysis, together with Russian grand strategy.

NPS-18-N376-A: Naval and Maritime Strategy

Researcher(s): Dr. James Russell, Dr. James Wirtz, Dr. Thomas-Durell Young, Dr. Donald Abenheim and Dr. Daniel Moran
Student Participation: LT Nathan Couric USN, LT Alex Turner USN, LT Ryan Clifford USN, and LT Athansios Varvoutis USN

Project Summary

The Navy is the midst of a sweeping re-organization to better enable it to connect its plans, programs, and policies to broader national and maritime strategy. The DCNO for Information, Plans & Strategy (N3/N5) is taking the lead in developing a new organizational structure to assist in this broad effort. The Department of National Security Affairs (NSA) has been actively supporting this effort in the N3/N5 through the Naval Research Program (NRP) for the last two years. In year one, a research team examined the Navy's existing processes of conceiving and executing naval strategy. In year two, a team of Naval Postgraduate School (NPS) researchers provided research and analysis to help various offices in the N50 with their tasks of helping design current and future strategy and the role that diverse global phenomena could have on future fleet design. In year three, NPS professors and a team of international scholars have delivered a series of analytical papers to address the relationship between high-level national strategy and the Navy's role in crafting a maritime strategy to meet national-level objectives. This effort is framed in Chief of Naval Operations (CNO) Admiral John Richardson's call for institution-wide innovation to meet emerging challenges facing the Navy on the high seas. The papers in this research report assist the N51 in ensuring that concepts of innovation will be centrally integrated into current and future fleet design as the Navy crafts a maritime strategy to meet national requirements.

Keywords: *strategy, programming, planning, budgeting, PBBS*

Background
The methodology for this study focused on upon qualitative research by the social scientists in the Department of National Security Affairs as well as those done by researchers at allied and coalition partner civilian and military institutions. This qualitative research focused upon the issue areas as requested by the N50 and, more generally, with the challenges facing the Navy ensuring that it builds innovation into designing its future fleet involving contingencies in a variety of different areas of operations.

To facilitate a broader discussion about the naval innovation, the report fleshes out the complex history of naval innovation over the 19th and 20th centuries, with particular attention focused on the Cold War and post-Cold War era.

Findings and Conclusions
Research report found that naval innovation is a complex phenomenon – echoing the findings of previous research into this subject area. It is not solely a function of technological advancement of particular systems that, in turn, can lead to new methods of operations. Such factors as institutional and organizational culture, bureaucratic politics, domestic politics, institutional intellectual traditions, dynamic leadership, and intra-organizational dynamics all affect the pace and character of innovation. Another important observation from the research is that, at its best, innovation often percolates from the bottom of organizations up to the leadership – functioning as a bottom-up process. It is a mistake to believe that innovation is driven from the top-down – a common belief in hierarchically structured military organizations. An important finding from the research is that the Navy must develop an organizational structure to foster bottom-up change and a human capital development strategy to ensure that innovation can spread within the organization outside the traditional avenues of authority in the hierarchy.

Recommendations for Further Research
Study represents another phase in an ongoing project to produce a series of research reports and volumes that can be used to help develop future leaders build a dynamic, innovative Navy. The School of International Graduate Studies, Department of National Security Affairs looks forward to continuing this work in the next fiscal year and beyond.

N4 - Material Readiness & Logistics

NPS-18-N014-A: Unmanned Surface Logistics Concept of Support

Researcher(s): Dr. Douglas Mackinnon, Dr. Paul Sanchez, and Dr. Susan M. Sanchez
Student Participation: LCDR Tai-shan Lin USN

Project Summary
The purpose of the Navy Supply Corps is to manage the logistical pipeline, so resources are delivered to the warfighter as required. Naval units are easily able to replenish their stores while they are in port, but difficulties can potentially arise when they get underway to conduct missions and training exercises. The use of unmanned systems introduces a new naval unit class with many beneficial characteristics, including autonomous control for which minimal human supervision is required, reliability demonstrated by International Regulations for Preventing Collisions at Sea (COLREGS), and spacious cargo transportability evidenced by enough topside space for a 20-ft. International Standardization for Organization (ISO) container. This thesis seeks to identify key influential factors and provide useful insights to logistically support naval readiness and the naval

units' continued ability to complete their missions. Modeling and analytical innovations used in this research include implementation of a discrete event simulation program, use of design of experiments, and sophisticated statistical analysis. Results from the analysis indicate that the rate of generation of new requests, the unmanned surface vehicle's top speed, and number of unmanned surface vehicles have the most impact on turnaround times for both mission duration and request fulfillment. Properly utilized, unmanned surface vehicles (USVs) can be a strong contributor to the success of U.S. Navy missions.

Keywords: *unmanned surface logistics, USV, Sea Hunter, ACTUV, DARPA, NRP, event graph model, discrete event simulation, design of experiments, JMP Statistical Analysis Program, NOLH, partition tree modeling*]

Background

Chief of Naval Operations, Admiral John Richardson's message last year on May 17, 2017, titled "The Future Navy" presented two consistent conclusions from studies and works conducted by many institutions. "First, the nation needs a more powerful Navy, on the order of 350 ships, that includes a combination of manned and unmanned systems. Second, more platforms are necessary but not sufficient. The Navy must also incorporate new technologies and new operational concepts." In order to support operations over a large area, naval logistics must be robust, versatile, and flexible. With the development of the unmanned surface vehicle, not only is there an additional unit with new technologies that can now be added to our current fleet force, a variety of choices and options can be considered for different employment and logistical concepts.

Past research with unmanned surface vehicles includes Casola's study on application via concept of distributed lethality, See's analysis of maritime interdiction missions, Toh's study looking at the computer's vision-based technique for situational awareness, and CAPT Kline and LCDR Solem's study on whether these unmanned units could perform better jointly with P-8 Poseidon aircraft in ASW-type situations.

Findings and Conclusions

This thesis uses a model-based approach to address these concerns, and a prototype discrete event simulation model is built to represent naval logistics operations. USVs are used to fulfill requests from requesting entities by transporting materiel from one of several Fleet Logistics Centers (FLC) to ship-designated rendezvous locations.

Six primary measures of effectiveness (MOEs) are considered: the "Average Number Requests in Queue," "Average FLC Utilization," "Average USV Utilization," "Average Mission Time," "Average Request Turnaround," and "Average Time of Unfilled Request." Eight factors are varied in a designed experiment to determine how strongly they influence the MOEs. The primary findings follow. For the "Average Number Requests in Queue," the new request generation mean contributes the most to its behavior. As the new request generation mean increases, the "Average Number Requests in Queue" increased as well. For the "Average FLC Utilization," the new request generation mean and onload service mean is able to explain the most about its behavior. For the "Average USV Utilization," the new request generation mean, the number of USVs, and the USV top speed contribute the most to its behavior. For the "Average Mission Time," the USV's top speed, the number of USVs, and the new request generation means explain the most about its behavior. For the "Average Request Turnaround," results from both revised and original models indicate that the same factors that affect "Average Mission Time" explain the most about its behavior. The "Average Time of Unfilled Request" is, unsurprisingly, strongly correlated with "Average Number Requests in Queue" showing unstable queuing conditions when exceeding an average of 1,000 in queue. There is also a strong direct proportion between these two MOEs when the "Average Number Requests in Queue" is close to zero.

Overall, the new request generation mean is a dominant force in straining the model. If too many requests are generated within a short period of time, the system does not handle this workload well. At their highest speeds, the USVs handle the majority of the workload generated by requesting entities. However, if the requests flood the system at an extremely high rate, the USVs will not have the capacity to handle all of the requests. Building more USVs alleviate the workload requests. At lower numbers of USVs, the new request generation means will have a more significant impact on the average mission times.

With this concept of operations for USVs, there are trade-offs that the decision maker must consider between maintaining flexibility in deliveries and the necessity of leveraging larger vessels. For example, building more USVs results in more units being able to handle better the generated requests from requesting entities. But, at some point, there is a level of saturation where the addition of another USV does not improve delivery times to the customer. Also, the small USVs are restricted based on their capacity and must leave those materiel it cannot handle for the larger, traditional Military Sealift Command (MSC) vessels.

Some important considerations can be derived from these primary findings. The generation of new requests could have significant leverage in how the model operates. With low levels of requests, the user can mitigate increased queue lengths by increasing USV speeds, increasing the number of USVs, or decreasing service times. However, as the rate of generation of new requests increases, the system begins to lose its robustness and will eventually not be able to handle the fast influx of requests. Future work must take this into consideration to decide what methods would be the best to handle this type of situation.

Decision-makers sometimes wonder about the implications of how selecting different shapes of distributions could affect the outputs for the models. Sensitivity analysis using partition tree modeling shows the shape of the gamma distribution to have little impact. From this, future researchers will not have to expend energies in trying to discern what specific shape distribution to apply to their work.

After studying the directional impacts of the factors on the MOEs, the decision-maker must understand the trade-offs involved in either increasing or decreasing any of the input factors. Based on the analysis performed, there was no single factor that could be adjusted unidirectionally to beneficially affect all MOEs. The decision-maker could make a more informed decision by understanding the level of trade-offs the changes could affect the outputs.

Prioritization of the queue brings to light another interesting consequence. The system was designed to prioritize high priority requests over lower priority requests. For example, even if the queue had built up a queue length of 30 low priority requests, if a single high priority request were to enter the system, the USV would be compelled to process that request over others. Although initially this will satisfy the requesting entity with the higher priority request, this prioritization causes other lower priority requests to sit in the queue for potentially a very long time. As a result, the requesting entity may have to upgrade what used to be a low priority to a higher priority request, duplicate orders may be placed into the system, or illegitimately, some entities may begin to order everything as high priority since they have lost faith in the system. As mentioned in the previous implication, this is not an ideal situation since flooding the system will serve to only stress the already unstable system leading to an eventual breakdown of the entire USV support system.

The basic concept of support using unmanned surface vehicles has been developed with this research. Based on the frequency with which requests are placed into the system by requesting entities, suitable levels for the number of USVs, speed of the USVs, the rate of onload of materiel, and the rate of offload to requesting unit values can be chosen to achieve desired performance goals. These can assist the Navy in determining issues such as what rate of demand the USV system can sustain and how the logistics support operations should be structured. With the significantly lower costs for building, operating, and maintaining these USVs, the Navy should consider augmenting the Military Sealift Command fleet with these units.

Recommendations for Further Research

Several aspects of the model could be enhanced by adding more detail. For example, Fleet Logistics Centers were treated as mostly a static object in this research. The FLC object could further be refined by applying standard inventory reorder policies, modeling the policy-driven supply levels of materiel, as well as appropriately decrementing the FLC inventory in response to delivery to USVs. The USV object could also be further refined by modularizing the cargo loaded in more detail inside the USV since the dimensions of the cargo will play a larger role due to restrictions in space and dimension. Another aspect is to adjust the request priorities from randomization with uniform, even distributions to distributions that emulate historical distributions to simulate something closer to reality. The geographical construct may also be improved. Instead of treating the area as a 2-D sandbox in the Pacific region, the same area could be treated as the surface of a sphere. Another recommendation is to add coastal regions as potential delivery points instead of limiting to middle-of-the-ocean points. Choices in the model were based on a greedy algorithm. In doing so, opportunity costs may have been missed. The model could be modified to perform a more effective analysis on alternative options. This model was also designed to process orders based on a first-in-first-out (FIFO) algorithm. A potential addition could be to allow USVs to be re-tasked, and the lower priority request to be returned to the request queue, if a higher priority request is received before loading commences. Incorporation of random, unpredictable events could make this study more realistic as well. Another recommendation is to consider a more balanced approach when leveraging USVs. This study focused solely on benefits of using these units. An appropriate mix of different types of logistical assets may need to be chosen instead to more robustly support fleet operations. Another recommendation is to create a user-friendly interface for the managers as an important step toward shifting paradigms from traditional thinking to more innovative approaches. Finally, a monitoring system against assigning high priority levels to non-critical parts may be potentially added to ensure the program is not abused.

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NPS-18-N026-B: Big Data Elevation of Supply Chain Vulnerabilities

Researcher(s): Dr. Douglas Mackinnon, and Dr. Ying Zhao
Student Participation: MAJ Jacob Jones USMC

Project Summary

The U.S. Marine Corps prides itself on the ability to successfully operate within a dynamic environment in an expedient and expeditious manner. To achieve power projection requirements, high states of aircraft, vessel, equipment, and personnel readiness are to be preserved. No small accomplishment, this burden lies heavily on supply professionals and the agility of the supply network in support of operating forces. Supply Chain Management (SCM) must cultivate dynamic supply chains, fluid as the maneuver units they support. Though military action is reactive at times, proactive preparations foster an ability to increase momentum and gain the initiative. SCM should also adopt a proactive mindset, forecasting readiness requirements through critical and balanced consideration.

The purpose of this quantitative research is to assess the supply chain network of a deployed Multi-Mission Vertical and/or Short Takeoff and Landing (MV-22) Osprey squadron, discover inefficiencies that exist, and make recommendations to increase supply chain productivity. Specifically, this study takes advantage of Microsoft Excel and big data (BD) techniques to sort through structured and unstructured data. Collaboration with the Department of the Navy (DoN) for requirements and attaining data sets will permit the application of Excel and Lexical Link Analysis (LLA), a text-mining software, to derive relationships between given data sets. Extraction of variables such as response times and aircraft part availability will measure SCM strengths and draw attention to deficiencies. Interpreted relationships helps determine opportunities, shortfalls, and favorable and unfavorable conditions within the organizational and intermediate maintenance levels of the Osprey supply chain. The results observed will be the basis for supply chain improvement recommendations and assist with enhancing DoN SCM productivity.

Keywords: *supply chain management, Department of Defense Supply Chain Management, big data, data mining, text mining, big data and supply chain management, MV-22 Osprey, MV-22 Osprey Supply Chain, Lexical Link Analysis*

Background

The philosophy of SCM is one approach many organizations embrace as a force multiplier. When suppliers, manufacturers, distributors, and vendors form a cohesive partnership, benefits throughout the supply chain can be recognized while minimizing unwanted consequences. Just as SCM provides positive outcomes for the private sector, so too can the government and Department of Defense (DoD) realize many of the same advantages.

The concept of SCM has grown over the past few decades, with organizations developing supply chain systems to increase competitive advantage. Ellram and Cooper, (2014) stated in a journal article that the definition of SCM is "a supply chain is defined as a set of three or more entities (organizations or individuals) directly involved with the upstream and downstream flows of products, services, finances, and/or information from a source to a customer, (and return)" (p. 9). Citing previous work 13 years earlier by Mentzer, Dewitt, Keebler, Min, Nix, Smith, and Zacharia, (2001) demonstrates the consistency that SCM has remained. Essentially organizations must collaborate with its supply chain partners and develop aligned strategic policy to recognize the benefits of SCM. As Mentzer et al., (2001) stated, the same holds true today: managers must visualize the supply chain not as independent organizations but as a network of nodes facilitating a system of interaction, each impacting the function of the whole. With this perception, the integration of each supply chain member is vital to the success of the supply chain.

To take advantage of the benefits SCM can produce, members must align processes and policies to foster a collaborative environment throughout the supply chain. Every member must integrate processes, aligning strategic activities to gain a competitive advantage. Each must believe in a philosophy where unity of effort is more productive than the efforts of individual members. The challenges organizations experience when developing a SCM model are those where collaboration is critical to the success of the supply chain and the enhancement of all participants within the supply system.

To optimize SCM, discover opportunities, and identify shortfalls, big data and business analytics (BDBA) can be applied to enhance supply chain processes (Wang, Gunasekaran, Ngai, and Papadopoulos, 2016). For this research big data (BD) will be defined as "a vast amount of data generated very quickly and containing a large amount of content. The characteristics of BD is based on the rule of 4 V: volume (a large amount of data), variety (any type of data), velocity (high changeability, dynamic of data), and value (assessment expressed by verification)." (Kościelniak and Puto, 2015).

Due to the challenges BD imposes, BDBA must employ complex methods to process and analyze the data to discover valuable information relevant to the organization. Wang et al., (2016) continued to discuss the importance of business analytics and the application of BD. The end-state of BDBA is to assist managers concerning decisions on all levels of an organization; strategic, operational, and tactical. By implementing BDBA, organizations can "improve visibility, flexibility, and integration of global supply chains and logistical processes, effectively manage demand volatility, and handle cost fluctuations." (Wang et al., 2016, p. 99). Hazen, Boone, Ezell, and Jones-Farmer, (2014) also argue that organizations that utilize data science, predictive analytics, and big data (DPB) do improve supply chain effectiveness. The key component of DPB Hazen et al., (2014) mentioned is the quality of data during the assessment. If the data is of low quality, the results of analysis will include high levels of inaccuracy or noise. This can be detrimental to organizations who would make decisions based on DPB. The quality of information flow throughout a supply chain is vital to enhance supply chain performance.

The mission of the MV-22, defined in the MV-22B Training and Readiness (T&R) Manual is to "Support the MAGTF Commander by providing assault support transport of combat troops, supplies and equipment, day or night, under all weather conditions during expeditionary, joint, or combined operations" (DON, 2010, p. 1-3). The focus of this research will be to assess the supply vulnerabilities or opportunities that present themselves between a MV-22 operational level (O-level) and intermediate level (I-Level) maintenance activities deployed on a Marine Expeditionary Unit (MEU). The squadron examined will be Marine Medium Tiltrotor Squadron (VMM) 264 when assigned to the 22nd MEU in 2016. VMM-264 was embarked on the U.S.S. Wasp from 26 June 2016 to 21 December 2016 and assigned to support U.S. Africa Command, U.S. Central Command, Sixth Fleet, and Fifth Fleet operations (P. Arensdorf, email to author. April 18, 2018). During the deployment VMM-264 participated in Operation ODYSSEY LIGHTNING and conducted operations in the Mediterranean and Red Sea areas of responsibility.

Findings and Conclusions

This project focused on two objectives: to assess how dynamic the supply chain was during an MV-22 MEU deployment, and discover potential opportunities to preposition MV-22 parts to maintain high aircraft readiness rates. To meet these goals the study leveraged Aviation Maintenance/Supply Readiness Report (AMSRR) documentation to assess organizational and intermediate level maintenance and supply activities. After receiving the MV-22 data from the Heavy Lift Helicopter Program Management Office, the data was preprocessed. This modified the supply documents for ease of information extraction and compatibility with LLA. Data analysis occurred applying Microsoft Excel and LLA to structured and unstructured data components.

Supply documents annotated on the AMSRR with initial status codes of “BA” (parts in inventory and being ready to ship), and “AS” (parts that were shipping) were isolated for investigation. Concentrating the research solely on these components allowed for detailed scrutiny of supply chain efficiency and removed those parts that experienced specific component shortfalls and were not readily available, such as contractual agreements or life expectancy inconsistences.

Shortfalls within this project lie with the accuracy of the data received. Results that will be uncovered and potential recommendations to enhance SCM will stem from the data provided.

Errors in the AMSRR documentation, such as erroneous estimated arrival times and invalid routing identification codes, should be evaluated prior to making SCM recommendations and conclusions.

The first answer to the sponsor's requirements was that SCM, overwhelmingly, did not behave as an agile network, adjusting and adapting to the needs of VMM-264. After analyzing a 92-day period, the supply documents reported on the AMSRR conveyed a supply network that was reliant on supply nodes located within the continental United States. Highlighting "BA" Not Mission Capable Supply (NMCS) parts, the research showed that 71.3% of the requisitions were sourced from the continental United States while DLA Europe, located in Germany, sourced only 0.19% of the requests. "BA" Partial Mission Capable Supply (PMCS) displayed similar sourcing rates from the United States, accounting for 73.6% of the components while none of the PMCS parts were sourced from DLA Europe or other European distribution centers. "AS" coded parts shared comparable results. "AS" NMCS and PMCS sourcing activities accounted for 83.4% and 72% of the components forwarded from the United States. None of the parts initially given a status code of "AS" were sourced within the European theater of operation.

The second sponsor requirement was to identify and recommend parts with possibilities to preposition. This project discovered nine outlier parts that were ordered at a higher frequency than the preponderance of the components demanded. Emphasizing parts that were originally categorized as "BA" and "AS", and critical to aircraft readiness, the research recognized those nine parts as maintained in the supply system, having the opportunity to be pushed to optimal supply chain locations based on mission requirements.

The study uncovered an opportunity for supply professionals to proactively engage supply chains supporting deployed units, confirming the rigidity of SCM. Not tethered to the MV-22 Osprey, this research and methodology could be used to assess supply chain agility across numerous platforms within the DoD. In this situation, applying BA analytics to supply documentation provided a descriptive evaluation of the supply chain. Employing predictive analytics to supply records would be an alternative study that could advantageous, assisting in SCM decisions.

Recommendations for Further Research

Follow on research to assess and increase SCM efficiency can be broken down into three subject areas: parts, locations, and inventory management. Focusing efforts to understand shortfalls and limitations with demanded components, supply warehouse locations, and methods of managing inventories will position supply chain professionals in a manner that will cultivate supply chain agility. Fostering agile supply chain management strategies will create a proactive rather than reactive supply chain response, resulting in improved readiness and increased combat capability.

Due to the robust nature of naval aircraft and equipment, an intimate knowledge of component lifespans and proper diagnosis of faulty parts and subsystems is a critical element to any supply system. Studies concerning failure rates of parts and engineering expectations may uncover additional supply chain vulnerabilities. Parts that are not identified or perceived as challenges will put un-do burden on the supply chain and decrease SCM effectiveness. This research could also consider maintenance actions repairing and diagnosing inoperative components. Assessing personnel habits and techniques to repair aircraft may unearth training deficiencies that negatively impact supply systems. Parts can also be grouped into subcomponents and subsystems to assess categories of parts and find inconsistencies or obstacles that may be occurring due to a specific subsystem rather than discrete components.

Another aspect to conduct research on would be to measure the efficiencies of each supply node. Analyzing each supply warehouse location and routing identification codes could provide additional insight to evaluate efficient locations. Through comparisons, research could uncover valuable information about location productivity, available space for stock, and shipping/transportation responsiveness. This could unearth reasons for the use of supply distribution originating from the continental U.S. Furthermore, information regarding host nation requirements, such as customs obligations, must be considered to ensure impediments are mitigated and do not add to supply chain delays. Making informed decisions regarding supply nodes and locations, supply chain professionals could real-time optimize the supply network depending on mission requirements.

Lastly, researching inventory management techniques and tools for supply warehouses and stockpiles could be beneficial to enhancing SCM effectiveness. Whether information technology systems are implemented to track and manage inventories, or locations manually account for inventories, various approaches to accountability could be assessed to determine the most resourceful. Again, supply professionals could modify inventory management methods to best fit each supply location benefiting the entire supply network.

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NPS-18-N038-A: Multi-Commodity Push/Pull Logistics for Distributed Lethality

Researcher(s): Dr. Michael Atkinson, and Dr. Moshe Kress
Student Participation: LCDR Stephen Mannila USN

Project Summary

Evolving anti-ship ballistic missiles are enhancing the effectiveness of anti-access (A2) strategies, which seek to keep opposing forces out of an operating area. This may reduce the effectiveness of legacy U.S. Navy operational principles, which rely on large, multi-ship carrier strike groups. In response, the Navy created an offensive principle known as distributed lethality (DL) that would allow warships to project power within an A2 environment. DL calls for smaller, agile, and lethal combinations of ships, called adaptive force packages (AFPs), which operate in a distributed manner over a large area. This concept brings about the logistical challenge of satisfying distributed demand across many locations. Moreover, the A2 environment poses a threat to the Navy's standard resupply source, the Combat Logistics Force (CLF) ship. CLF ships, with their relative large signature as targets, can no longer afford to travel close to forward deployed forces without being subject to effective missile attacks. These developments require modifications in the Navy's

combat logistics chain. This project proposes and analyzes a modified Navy combat logistics chain aimed to support small - and medium-sized warships operating as AFPs within a DL and A2 environment. It also analyzes requirements for the development of mini-CLF ships as the main AFP resupply source.

Keywords: *Distributed Maritime Operations, logistics, simulation*

Background

Anti-access strategies, which seek to keep opposing forces out of an operating area, have been enhanced by improvements in anti-ship ballistic missile (ASBM) technology. The risk to large ships or even groups of ships may reduce the effectiveness of U.S. Navy legacy principles, which rely on large, multi-ship carrier strike groups. Responding to this challenge, the Navy developed a more offensively oriented principle known as distributed lethality (DL) that would allow warships to project power within an A2 environment (Rowden, Gumataotao, and Fanta, 2015). DL calls for smaller, agile, and lethal combinations of ships, called adaptive force packages (AFPs), which operate in a distributed manner over a large area. This concept brings about a logistical challenge: how to satisfy customer demands that are potentially distributed across many locations and dispersed over a large, possibly contested, area. Moreover, the presence of ASBMs poses a significant threat to the Navy's standard resupply source, the Combat Logistics Force (CLF) ship, which poses a large signature as target. CLF ships can no longer afford to travel with, or even operate close to, forward deployed units. These developments in the operational posture require modifications in the Navy's combat logistics chain.

In this project, we propose and analyze a modified Navy combat logistics chain aimed to support small- and medium-sized warships operating as AFPs within a DL and A2 environment. We also analyze requirements for the development of mini-CLF ships as the main AFP resupply source. Our model focuses on logistical flexibility, which facilitates rapid and efficient transfer of logistic resources among widely dispersed demand locations. Similarly to the idea of "risk-pooling" in commercial supply chains, the idea here is to concentrate resources at a centralized location outside of the immediate operating area and project logistics forward as needed. This enables the logistics chain to satisfy fluctuating demand over a wide area (Kress, 2016). Mini-CLF ships operate outside of the combat zone at the aft of the replenishment-at-sea lane, but within the A2 threat area. AFPs travel from their forward operating stations to the aft of the replenishment-at-sea lane for replenishment. CLF ships operate outside of the A2 threat area and can provide replenishment support to mini-CLF ships and AFPs. AFPs, mini-CLF ships, and CLF ships each have their own priorities for commodity replenishment depending on the commodity, the operational posture, and the availability of ports, mini-CLF ships, or CLF ships for replenishment. Our objective is to assess the feasibility of using mini-CLF ships as the main resupply source for AFPs operating in a DL and A2 environment.

Mentioned earlier, our approach relates to the concept of inventory pooling, which combines the inventory from multiple locations into fewer locations that carry a larger amount of inventory (Ferrer, 2017). Our study treats a port or CLF ship as the manufacturer or a large warehouse in a commercial supply chain, the mini-CLF ship as the distributor, and the AFP as the customer. We concentrate resources outside of the combat area, with one or more mini-CLF ships who can each service multiple customers depending on the demand. By merging (pooling) the demand, the overall effect of demand uncertainty may be reduced. One important consequence of the uncertainty (variance) reduction is that safety stocks levels may be reduced. The idea is to replace mass (of supplies) with agility (of mini-CLFs).

The use of mini-CLF ships as shuttles between CLF ships and Navy warships was first studied in a Naval Postgraduate School thesis written by Colburn (2015). He developed a network based linear program that prescribes the optimal at-sea replenishment schedule for Navy warships, mini-CLF ships, and CLF ships operating within an ASBM A2 environment. Mini-CLF ships are smaller and therefore considered safer from being destroyed by the DF-21D ASBM due to their relatively small signature. While we utilize the same at-sea replenishment network and the mini-CLF ship concept as in Colburn (2015), our study significantly extends the modeling and analysis in Colburn (2015) by (a) introducing stochasticity – many parameters in a combat scenario are random variables, and (b) considering multiple commodities, and (c) modeling combat attrition.

Findings and Conclusions

Our model accounts for multiple commodities, such as distillate fuel marine, jet propellant-5, stores, and ordnance, which compete for storage and transportation capacities. We also assess the survivability of the logistics chain by introducing port and mini-CLF ship attrition while inside the A2 environment. To accomplish this, we developed a stochastic simulation model that emulates the performance of the resupply network under varying scenarios and mini-CLF ship configurations. Attrition is defined as the probability of non-survival of a vulnerable port or mini-CLF ship by the end of a 60 days period. We assume that each day, each mini-CLF ship or port still in operation is destroyed with a certain probability, and these events are independent across days, mini-CLF ship, and port. Our first measure of effectiveness (MOE) is the fraction of time an AFP is on-station and operating above its commodity safety levels. When an AFP crosses a commodity safety level, it seeks replenishment of its commodities. The second MOE is how often AFPs cross commodity extremis levels. AFPs are at risk of running out of commodities when it crosses an extremis level. The difference between the safety and extremis levels is the urgency in which resupply is needed.

Operating scenarios considered in our study are divided between peacetime, with a 180-day time horizon, and wartime, with a 60-day time horizon. They are further divided by ASBM ranges of 1,000 NM and 2,000 NM. Although our model is not based on a real-world operating area, we vary notional geographic characteristics, such as the distance between operating stations, ports, and replenishment-at-sea lanes, to assess their impact on our MOEs.

Our preliminary analysis shows that mini-CLF ships are a feasible option to support AFPs operating in a DL and A2 environment. We observe that the number of mini-CLF ships operating in theater has a greater impact on the operation of AFPs, in terms of our MOEs, than the cargo capacity of a mini-CLF ship. As a result, we recommend a one-to-one ratio of mini-CLF ships to AFPs during peacetime scenarios. During combat operations, with moderate level of attrition, the number of mini-CLF ships should be one plus the number of AFPs. Interestingly, these numbers are relatively insensitive to the cargo capacity of the mini-CLFs. As a result, we recommend the smallest possible cargo capacity, which translates to smallest possible physical footprint. The cargo capacity of a mini-CLF should be enough required to replenish the largest AFP after it reaches 10% below all of its commodity safety levels. This configuration has storage requirements that are only 28% of a Fast Combat Support CLF ship for liquid fuel and 13% for stores and ordnance.

During peacetime there is very little need for the (legacy) CLFs; ports are secured and thus always available for replenishing the mini-CLFs. The need for CLFs for replenishing the mini-CLFs increases in wartime scenarios due to the increased usage of ordnance by AFPs. Also, if ports are removed from the logistic network due to attrition, then, obviously, CLF ship usage increases significantly.

We find that as the range of ASBMs increases, AFP performance, in terms of our MOEs, decreases. This is because mini-CLF ships need to travel longer distances to the CLF ship, which has to be stationed farther away from the combat zone to reduce its vulnerability to the ASBMs. The extended travel time for the mini-CLFs increase the length of the supply cycle and thus reduces the availability of the mini-CLFs. In wartime, destroyers and cruisers carrying guided missiles have to transit to ports outside the threat area for vertical launch-system weapon replenishment.

Combat attrition may have a significant negative impact on AFP performance, but this impact can be mitigated by the introduction of additional CLF and mini-CLF ships. Finally, we note that the utilization rate of an AFP containing a littoral combat ship (LCS) is up to 20% lower than an AFP without an LCS. This is due to maintenance requirements for the LCS that are performed in ports.

Recommendations for Further Research

The geography utilized in our simulation model is generic and is not based on any specific theater of operations. To improve on the operating characteristics of the mini-CLF ship concept, we recommend theater specific AFP compositions and safety levels, as well as adapting the geography of the model to specific theaters.

During wartime scenarios, the need to replenish vertical launching system (VLS) weapons can take a ship carrying guided missiles off station for a significant amount of time because it has to transit to a friendly port. Integrating a notional at-sea replenishment system into the model can help determine the value of developing this capability.

Mini-CLF ships with a limited self-defense capability do not need to rely solely on AFP warships for defense. This may allow additional employment methods of mini-CLF ships such as allowing it to transit to the AFP station or travel with an AFP as a station ship.

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NPS-18-N307-A: Evaluation of USFF's Environmental Outreach Initiatives

Researcher(s): Dr. Gail F. Thomas, Dr. Kimberlie Stephens, Dr. Jessica Neff and Ms. Sally Baho

Student Participation: No students participated in this research project.

Project Summary

This Naval Research Program (NRP) project evaluated US Fleet Forces Command's (USFF) environmental assessment program. This study addressed five questions:

1. What is the best practice guidance from the extant literature about environmental outreach program evaluation? *Deliverable: U.S. Navy Environmental Outreach Evaluation Guidebook*
2. Using environmental assessment best practices, how robust is USFF's environmental outreach assessment. *Deliverable: Assessment of USFF's Environmental Outreach Program 2014–2017*
3. How USFF might improve their media analysis to better achieve their objectives and desired stakeholder effects? *Deliverable: Media Daily Clip Tracking and Coding System*
4. Do existing activities measures of performance (MOPs) link to desired stakeholder effects measures of effectiveness (MOEs) and commander's intent? What environmental assessment dashboard might be relevant for planners and leaders? *Deliverable: Evaluation of Existing Tools and Platforms*
5. What are the perceptions of selected regulators about U.S. Navy environmental practices? *Deliverable: Regulator Survey Results*

The study's output includes: An *Environmental Outreach Guidebook* that can be used across the US Navy to better plan and execute their environmental outreach programs. It draws on national best practices and exemplars in outreach assessment. Second, using standards from the *Guidebook*, we provided a systematic evaluation for four years of USFF's environmental outreach assessments, 2014-2017. This part of the study provides strengths and suggestions for USFF's environmental outreach program improvement. Third, we developed a daily media clips tracking and coding system as a way of monitoring environment-related issues that could predict concerns and influence Navy operations for leading, lagging, and coincident measures. Fourth, we developed a procedure to evaluate return on investment for outreach activities as well as an example dashboard that could be useful for senior leaders to monitor and assess outreach programs. Last, we facilitated the development and implementation of a regulator feedback system that would allow USFF to better understand how these important stakeholders view USFF's efforts.

Keywords: *environmental, outreach, program evaluation, media trend analysis*

Background

USFF implemented a formal environmental outreach program in 2013. Their strategy is designed to reach key stakeholders with fact-based messages about Navy environmental policy and efforts. The desired end state is increased support amongst the public, environmental regulators, non-government organizations (NGO)s and scientific and regulatory communities for USFF and Navy at-sea training activities and basing actions. USFF's outreach strategy is to determine its effectiveness and has expanded over the recent years from a local/regional focus to a national focus.

Research of local, national, and global news, including reviews of internet blogs and social media sites, has indicated that in recent years, well-funded NGOs have devoted considerable amounts of time, effort, and money to broadcasting the negative impacts of Navy training at sea, particularly with regard to the use of active sonar. Also of great interest to them has been alleged negative health effects of jet noise and the intentional harming of marine life via ship strikes and live fire exercises. Litigation against the Navy has been their weapon of choice.

For obvious reasons, misperceptions and misinformation have the potential of negatively affecting Fleet training activities and operational readiness (e.g. stricter regulations, injunctive relief, and negative comments on environmental planning documents).

Each year USFF conducts an annual assessment and evaluation of their environmental outreach program. With several years of data, USFF wanted an outside evaluation of their assessments with a desire to take program assessment to the next level.

Findings and Conclusions

This NRP project was designed to evaluate USFF's environmental outreach program and provide suggestions for improving their programmatic efforts. The idea is to use this as a model for all Navy environmental outreach efforts around the world. To accomplish this end, we addressed five study questions and provided associated deliverables.

SECTION 1: US NAVY ENVIRONMENTAL OUTREACH GUIDEBOOK

RQ1: What is the best practice guidance from the extant literature about environmental outreach program evaluation?

The *Environmental Outreach Guidebook* draws from best practices in program evaluation. Our research team conducted a literature search as well as examined organizations that are seen as exemplars in outreach assessment. Because of our search, we developed a short guidebook that can be used by Environment Outreach Programs across the US Navy.

Outreach evaluation is the systematic assessment of how outreach activities affects program goals. Evaluation provides an opportunity to identify strengths and weaknesses of current activities, to critically evaluate how activities and programs are (or are not) having an impact on high priority stakeholders, and to generate concrete recommendations for improvement in outreach activities.

Common questions that serve as the foundation of any evaluation effort include:
1) Did we meet our objectives?
2) Did we have an impact?
3) Who benefits from the evaluation?
4) Should our efforts be continued and/or replicated elsewhere?

Effective evaluation involves inquiry and learning, and the results provide a foundation for informed decision-making. Ultimately, program evaluation informs good resource management. The *Environmental Outreach Guidebook* provides a systematic process for developing a logic model that links inputs to activities to outputs, outcomes, and ultimately to impact.

SECTION 2: ASSESSMENT OF USFF'S ENVIRONMENTAL OUTREACH PROGRAM 2014-2017
RQ2: Using environmental assessment best practices, how robust is USFF's environmental outreach assessment.

The Naval Postgraduate School research team undertook a systematic review of USFF's assessment strategy for environmental outreach efforts. We reviewed four years of Environmental Outreach End-of-Year (EOY) assessments, along with a wide range of supplemental documents, and conducted a series of in-depth interviews. This allowed us to gain a deep understanding of how USFF's assessment strategy has evolved over time and to determine the strengths and weaknesses of current efforts.

We included a rating of USFF's efforts on each step in the framework for the past four years. This longitudinal analysis provides insights into which areas have been improving over time, and which have remained at status quo. We also included concrete recommendations we believe will allow USFF to improve their environmental outreach strategy.

SECTION 3: DAILY MEDIA CLIPS TRACKING AND CODING SYSTEM
RQ3: How might USFF improve their media analysis to better achieve their objectives and desired stakeholder effects?

Effective tracking and evaluation of strategic outreach efforts requires regular monitoring of vast and widespread sources of data. From traditional media to social media to public comments, opinions and perspectives of stakeholders are being constantly shared. This media demonstration project takes one of USFF's regular sources of data, daily news clips, and provides a simple, yet powerful means of tracking changes in volume, content, and coverage over time.

The USFF press clip process is robust in its regularity and reliance on deep tacit subject matter expertise. The simple process allows clippings to be updated to include new and emergent topics and the in-email text allows quick and easy perusal of media conversations. The current process is limited, however, in its ability to look across time and at trends in topic coverage. This makes alignment of this information with trends in other data sources, such as public comments, or legal or legislative activities, as well as alignment with communication strategy more difficult.

To demonstrate the increased analytical power of compiling the daily clips into a single data set, we created an excel template that can be used as the basis for beginning to monitor trends over time. The sheet we created requires that the basic pieces of information from each article (title, byline, source, text, etc.) be inserted into the sheet and then using formulas, each article is automatically coded for a set of topics. These topics can be updated, expanded or deleted over time to keep up with changing needs and results can be depicted in charts or tables to create a shared understanding of stakeholder perceptions.

SECTION 4: TOOLS FOR EVALUATING ACTIVITY IMPACT - ROI AND DASHBOARD

RQ4: Do existing activities (MOPs) link to desired stakeholder effects (MOEs) and commander's intent?

What environmental assessment dashboard might be relevant for planners and leaders? Assessment of outreach efforts requires evaluation of return on investment of individual outreach activities. This deliverable provides a set of exercises to help USFF assign an ROI to ongoing activities.

The exercises provide five steps:

1. Develop theories of stakeholder change as a result of USFF Outreach activities
2. Generate hypotheses about the link between USFF activities and stakeholder impact
3. Track activity outcomes using the stakeholder tracking chart
4. Assign resources to individual activities
5. Compare outcomes of stakeholder changes relative to resources invested

As requested by the sponsor of this study, our results can be used to upgrade USFF's environmental assessment program. We have identified specific strengths and areas for improvement and provided several tools that could be implemented in their data gathering, trend analysis, and assessment efforts.

SECTION 5: REGULATOR SURVEY FEEDBACK

RQ 5: What are the perceptions of selected regulators about U.S. Navy environmental practices?

Important to USFF's effort are the approvals that are given by national, regional, or local regulators. Our research team facilitated the development of feedback instrument that was administered to selected regulators. The purpose of this part of the study were fivefold:

- Evaluate the effectiveness of the Navy's efforts to inform regulatory agencies of the impact its training and testing activities have on the environment.
- Assess perceived strengths and weaknesses relevant to collaboration during consultations.
- Determine if the Navy has been successful in demonstrating its commitment to incorporating environmental stewardship into testing and training efforts whenever possible.
- Identify subject matter areas in which the Navy could improve recognition of expertise and capabilities.

Recommendations for Further Research

Future research could be conducted to further develop and test traditional and social media algorithms. Additionally, operations research analysts or economists could further develop a ROI model that could more adequately assess a program's effectiveness.

NPS-18-N337-A: Development of Nanoparticle Formulations for Alternative Metal Additive Manufacturing Routes

Researcher(s): Dr. Claudia Luhrs
Student Participation: LT Farsai Anantachaisilp USN, and LT Gabriel Supe USN

Project Summary
The research conducted had the objective of developing an additive manufacturing (AM) strategy to produce metal or alloy parts through the use of layer-by-layer extrusion of small particle paste formulations along post-processing steps. That is, we aimed to hybridize additive manufacturing approaches with known powder metallurgy (PM) processes to produce alloys of naval relevance. The work that we are reporting herein generated metal parts using, instead of expensive direct sintering equipment (metal tri dimensional (3D) printer), a conventional 3D printer (as the ones used for polymeric filaments). The later was equipped with an extruder capable of deliver paste composed of metal nano or micron particles and binding media that evaporated after the printing operation was completed. The 3D parts produced using those paste formulations had similar characteristics that the ones observed in green specimens generated by PM. Using the same type of post-treatments that AM and PM routes employ, such as annealing and hot isostatic pressing (HIP), we were able to generate 3D specimens of NiTi and NiCu alloys. We demonstrated that the new process could successfully generate solid specimens, which, after HIP operations, showed mechanical robustness. This new approach could be easier to adapt than laser or e-beam sintering routes and has potential to be used for metal/alloy parts that do not require stringent load bearing specifications.

Keywords: *metal additive manufacturing, paste formulations, AM, powder metallurgy*

Background
Additive manufacturing (AM) techniques to fabricate metal parts require lasers or electron beams to produce localized melt or sintering of the raw powder, allowing the layer-by-layer fabrication of complex components. The resulting build has to be heat treated after printed to produce the final microstructural features and be able to reach the desired mechanical properties. Despite the advantages of AM of metals, the instrument and operational costs are still very high.

Powder metallurgy refers to techniques that allow the fabrication of consolidated parts from metal powders that are compressed into the desired shape. The result is a green specimen that requires annealing in controlled atmospheres to join the particulates.

AM and PM techniques share some characteristics: a) small size particulates are employed as the raw material, b) builds generated require post-processing (annealing or hot isostatic pressing) to achieve the desired microstructure, reduce porosity and gain the targeted mechanical properties, and c) since no tooling or material removal is required, costs can be drastically reduced when compared with other fabrication approaches.

Developing a hybrid technique that uses paste composed of metal powder to create parts layer-by-layer to then sinter or hot isostatically press them to imprint the desired properties and microstructure expands the type and complexity of parts that can be produced. Operational sites that could not afford a metal printer and do not have stringent load bearing requirements could greatly benefit from the proposed manufacturing approach.

Findings and Conclusions
Nano and micron size particulates of Ni, Cu and Ti were mixed to generate NiTi or NiCu alloy parts. The fluid component of the paste that presented the optimal consistency to be 3D printed along the

metal particulates was a mixture of water, ethanol, and a thickening agent. Other liquid phases, such as ethylene glycol and a mixture of semi-solid, saturated hydrocarbons, mainly of paraffinic nature, were also tested. The post treatments including furnace annealing at temperatures between 800-1000 degrees C and hot isostatic pressing at 1000 degrees C at pressures between 20-30 K psi. The samples crystalline components were identified by X-ray diffraction, their microstructures and degree of porosity studied by optical and electron microscopy. Hardness tests served as initial indication of mechanical properties and tensile tests as a more complete evaluation.

The research conducted provided a proof of concept that alloy solids can be 3D printed using affordable polymeric printers; however, post processing steps are needed to reach the desired mechanical values.

Recommendations for Further Research

This research demonstrated that the new process could successfully generate solid specimens, which, after HIP operations, showed mechanical robustness. This new approach could be easier to adapt than laser or e-beam sintering routes and could be applied for metal/alloy parts that do not require stringent load bearing specifications. Next steps include the fabrication of complex shapes and treatments at higher HIP pressures/temperatures.

NPS-18-N337-B: Novel Low Temperature Chemical Process for Metal AM

Researcher(s): Dr. Jonathan Phillips
Student Participation: LCDR Chris Pelar USCG

Project Summary

Using a version of the Reduction Expansion Synthesis (RES) process, micron scale chromium (Cr) coatings were generated on iron wires. The process involves these steps: I. A paste was created from a physical mix of urea, chrome nitrate or chrome oxide, and water. II. An iron wire was coated by the wet paste, simply by mechanical dipping. III. The coated wire was heated to ~800 °C for 10 minutes in a tube furnace under a slow flow of inert, e.g. nitrogen, gas. The processed wires were characterized, primarily with scanning electron microscopy (SEM), and found to be evenly covered by a non-porous metallic chrome layer. Additionally, it was found that thickness of the final Cr layer correlated with the thickness of the precursor layer that was applied prior to the heating step. The significance of this finding for metal additive manufacture (M-AM) is that it represents the first step in creating a non-porous metal from a viscous paste at 'low' temperature. Following steps will require printing with the paste into the desired geometry, and then heat treating.

Keywords: *metal, additive manufacturing, Reduction Expansion Synthesis, chrome, coating*

Background

The present commercially available tools for M-AM are very expensive (>$100,000), always require extensive post-processing equipment and time, require significant training and operator experience, and only function in a stable physical environment. All of these characteristics make deployed operation of metal additive manufacture (M-AM) difficult for the U.S. Navy and Marines. This research is intended to create an inexpensive M-AM (<$5000) that only employs devices already demonstrated in deployed operation.

Findings and Conclusions

A chemical method (Cr-RES) for making multi-micron thick, pore free, metallic chrome layers from an inexpensive precursor paste, at a relatively low temperature, was demonstrated. Step I: The first part of the coating process is creation of a paste consisting of a physical mixture of water, urea, and micron scale chrome oxide powder. A mixture of urea (Aldrich 99%) and chrome oxide in a 2:1 weight ratio was pulverized in a mortar and pestle. Distilled and deionized water was added until a 'wet paste consistency' was achieved. Step II: An iron wire (0.1 cm diameter, Aldrich 99.99%), was bent to form an open rectangle, and then polished. Dipping was employed to coat the wire with precursor. The coating was then air dried for several hours. Step III: The coated wire was placed in an open top alumina 'boat', and the boat then positioned at the center of a 1.5 "diameter quartz tube. While flushing with inert gas, the tube was placed in a clam-shell style laboratory tube furnace, pre-heated to 800 C. After 10 min, the quartz tube/wire was removed from the furnace, and allowed to cool. Step IV: The cooled wire was covered with a light grey 'ash', which was removed with light hand polishing. Detailed studied using Scanning Electron Microscopy clearly showed that a pore free chrome metal layer was only found where the paste was deployed. In essence this is a form of 3D metal printing. To wit: Metal is produced from a 'wet' precursor that can be molded/painted/ printed to a particular shape. In this study that shape was a thin coating of a 'wet' chrome containing mixture 'painted' onto a metal wire. After curing, a metallic chrome thin film (same shape) remained.

Recommendations for Further Research

The success of this method suggests a path forward for developing an RES based process for metal additive manufacturing using low cost tools. In fact, the success suggests further research designed to create a protocol for making metal objects at low temperatures employing only a standard plastic 3 D printer (~$1000), and a typical electric furnace (~$3000) could lead to a dramatic reduction in the cost and complexity of M-AM. There could be many advantages to the U.S. Navy in terms of cost, training time, and operational compatibility with ship and shore platforms. Indeed, present generation M-AM requires a tremendous initial investment (>$100,000) in special precursor powders, significant training, and high stability environments.

It is notable that the results were predictable given current understanding of the RES process, a process developed by Naval Postgraduate School engineers, and extensively described in the literature (1-6).

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NPS-18-N355-A: Additive Manufacturing in Naval Domain: Innovation, Adoption and Taxonomy of Cybersecurity Threats

Researcher(s): Dr. Amela Sadagic, and Ms. Kristen Tsolis
Student Participation: LCDR Michael Grimshaw USN

Project Summary

A growing potential and promise that additive manufacturing (AM) brings to the naval domain is matched with a set of activities focused on service members' innovation, experimentation and rapid prototyping with a range of technologies including AM. Increased level of warfighters readiness and self-sustainment in Department of Navy (DoN) operations are at the center of those efforts. We investigated select elements of innovation and adoption process, and added much needed understanding in domain of cybersecurity. Our research included collaboration and visits to Naval Fabrication Laboratories (FabLab), Maker spaces and units with AM capabilities. We collected a comprehensive data sets relevant to innovation, adoption and cybersecurity, and documented examples of innovation efforts done by the Sailors and Marines. The work produced a set of recommendations with guidance directed towards most effective approaches in support of bottom-up innovation process, large scale adoption strategies, elements of self-sustainable and scalable adoption process, guidance for distribution of efforts, resources and programs, as well as management of cybersecurity infrastructure and needed approaches, all geared towards achieving maximum use of the technology and innovation practices without sacrificing on cybersecurity. The results of this work - data points and insights acquired through our work with the stakeholders - are used to further refine our model of Diffusion of Innovation in Military Domain.

Keywords: *additive manufacturing, cybersecurity, 3D printing, fabrication laboratory, rapid prototyping, diffusion of innovation*

Background

The potential that additive manufacturing brings to the naval domain, and military domain in general, is well recognized; AM technology continues to improve in terms of variety and sophistication of 3D printing techniques, quality of printed artifacts, and scale (size) of printed artifacts. A 30 foot long 3D printed proof-of-concept submersible, developed by a team from the Naval Surface Warfare Center (NSWC) and Carderock Division's Disruptive Technology Laboratory (DTL) and produced using massive industrial 3D Pinter called Big Area Additive Manufacturing (BAAM), as well as very recent example in August 2018, when the world's largest concrete 3D printer was used to construct a 500-square-foot barracks hut at the U.S. Army Engineer Research and Development Center in Champaign, Illinois (effort led by Marine Corps Systems Command), are the best illustrations of the scale of advancement that AM technology currently enjoys. As the Navy increases its AM portfolio and expands implementation of this time, cost, and energy saving technology, there is increased need to ensure that this technology successfully engages a large number of innovators and that the data they produce and manipulate throughout the AM workflow are secure as well.

The characteristics of the innovation and benefits it brings to its users are important elements that influence adoption of that innovation among its intended users (Rogers, 1995). Additional elements that significantly impact the rate of adoption are user-perceived usefulness of innovation, its ease of use and final user acceptance - these characteristics were studied and incorporated in Technology Acceptance Model (TAM) introduced by Davis, (Davis, 1986)(Davis, 1989)(Davis, 1993), as well as Venkatesh (Venkatesh, 2000). A new theory - Unified Theory of Acceptance and Use of Technology or UTAUT - also incorporate these types of considerations (Venkatesh, 2003). Adoption of any new technology, idea, process or other solution can engage different number of individuals who operate in a given domain. The reason why a large-scale adoption remains of special interest is "...the collective change in the way adopters act and behave once the adoption occurs on a large scale, and the potential that such a change may bring to them and their community" (Sadagic, 2015).

Findings and Conclusions

The following methodology has been proposed and used in support of this research project and included the following activities:

1. Study of literature in the domains of innovation, technology adoption, and cybersecurity threats in AM (digital thread framework).
2. Cataloging and development of cybersecurity taxonomy in AM. Identification of issues, concerns, tools, data sharing strategies, potential vulnerabilities and collaborative processes. Research in this domain was reported in a student thesis (LT Grimshaw).
3. Field visits to Fabrication Laboratories, Maker spaces, units that own AM capabilities, as well as base commands and other institutions relevant to AM activities in the naval domain. Major goal: enable face-to-face discussions with colleagues and support data collection efforts.
4. Work with the Naval Postgraduate School (NPS) RoboDojo laboratory and execution of a series of focus groups and activities with NPS students (active duty Department of Defense (DoD) officers and international students) and faculty.
5. Data collections organized in Fab Labs, Maker spaces and Department of Navy (DoN) units, focused on innovation, adoption and cybersecurity.
6. Practical work and experience with a range of devices associated with AM and Fab Labs.
7. Collaboration with NPS Modeling, Virtual Environments and Simulation (MOVES) colleagues who work on implementing data portal, and study of its adoption and use by naval personnel.
8. Collaboration with stakeholders in this domain, including our topic sponsor DCNO for Material Readiness & Logistics (N4), Naval Facilities Engineering Command (NAVFAC), National Institutes of Health (NIH) and industry representatives. The project Principal Investigator (PI) participated in monthly teleconferences organized by the topic sponsor's team.
9. Collaboration with forums and other colleagues who actively work in the AM domain.
10. Design of theoretical and methodological principles (development of Diffusion of Innovation in Military Domain model).
11. Design and development of the instructional modules to be made available to NPS students and faculty, as well as materials produced to support activities in the Fab Labs (manuals that documented our experiences with 3D scanning and 3D printing technologies). Resulting manuals were written having in mind the needs and skills of a large majority of Sailors and Marines – individuals who have limited technical knowledge and no prior experience with 3D printers and 3D scanners. The same manuals were made available to Fab Labs across the naval domain.

Events supported: The project team supported and actively participated in the following events:

1. Institute of Electrical and Electronics Engineers (IEEE) Virtual Reality (VR) 2018 conference in Reutlingen, Germany (18-22 March): Dr. Sadagic was a member of International Program Committee for this conference.
2. Naval Research Working Group - NRWG 18 (10-12 April, 2018): Dr. Sadagic presented several posters that highlighted the work on the project and illustrated the activities of the AM team at NPS. She also supported two lab tours and introduced project activities to the visitors (10 April and 12 April).
3. MOVES Research Working Group (MAWG) - MAWG event organized by MOVES Institute in May 2018. Dr. Sadagic presented a talk titled "Additive Manufacturing in Naval Domain: Large Scale Adoption and Innovation by Masses of Domain Users." She also produced two AM-themed posters, hosted a lab tour, and introduced AM research efforts conducted by MOVES faculty.
4. Interactive 3D Content Embedded into Web Pages (WEB3D) 2018 conference in Poznan, Poland (17-20 June, 2018). Dr. Sadagic was a Program Committee Member for this conference.
5. Discover NPS Day (Dec 1st, 2017): Dr. Sadagic designed a number of demo stations that were made available to NPS visitors in MOVES laboratories. They included one 3D printer (this was

made operational on the day so that visitors could see the way 3D printing works), AM-related posters developed for the needs of our project, and a number of 3D printed objects. Final demos were supported by Dr. Sadagic and three other project team members – Erik Johnson, Ryan Lee and Eric Heine, as well as a number of MOVES students. The elements of this project will be featured during upcoming Discover NPS Day on Oct 26, 2018.

Recommendations for Further Research

The adoption of any technology by masses of intended users is a process that happens over a longer period of time. A need to commit to and execute a series of longitudinal studies and data collection efforts, is inevitable part of the work in this domain.

We propose following research activities:

1. New round of data collection: Data collection efforts should continue to be organized; they should include data from users (adopters, innovators, leadership of all levels) and fabrication labs.
2. Definition of metrics and measurement of adoption process: Over the course of this project we acquired initial understanding about the metrics that can be used to measure the success of the adoption process. New research should include more extensive effort in this domain.
3. Comprehensive study of return on investment (ROI).
4. Additional functionality in the ModelExchange portal: We recommend continuing collaboration with colleagues who work on the ModelExchange portal.
5. Refine our model of Diffusion of Innovation in Military Domain.

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NPS-18-N380-A: Naval Additive Manufacturing X3D Model Exchange: Preliminary Operational Capability

Researcher(s): Dr. Don Brutzman, Mr. Terry Norbraten, Mr. Joseph Bailey, and Dr. Rebecca Law
Student Participation: Capt Matt Friedell USMC

Project Summary

The Naval Postgraduate School (NPS) has applied and integrated a wide range of open-source open-standards capabilities to support Navy and Marine Makers who are learning and applying three-dimensional (3D) printing, also known as additive manufacturing (AM). Building on the work of the National Institutes of Health (NIH) 3D Print Exchange (3dprint.nih.gov), the Extensible 3D

Graphics International Standard (X3D) Model Exchange (ModelExchange.nps.edu) enables Navy and Marine Makers to learn how to find, share, produce, and print 3D models that impact the future of Navy and Marine operations. Whereas the NIH site is built using Drupal 7 with a "pipeline" for processing uploaded models, the Navy's X3D Model Exchange is developed with the latest version of the Drupal 8 Content Management System (CMS). This public-facing portal leverages the highly evolved NPS version-control repository (GitLab.nps.edu/ModelExchangeGroup) using best practices for Agile-software Development Operations (DevOps) progress to encourage broad partnerships and re-use. Security requirements are met through account management and Common Access Card (CAC) authentication of users. Version control ensures that all changes and incremental improvements are trackable, repeatable and fixable (if ever needed). Access control for administrators, developers, makers and the public ensures that models remain uncorrupted and only available to the appropriate community of users. This project reports on follow-on continuation of the design phase performed by preceding Naval Research Program (NRP) project NPS-17-N244-A.

Keywords: *3D printing, additive manufacturing, community, digital thread, X3D graphics, Web3D*

Background

AM, 3D printing and computer-aided design (CAD) export are critical for Navy maintenance. Rapid change continues to occur across the design, engineering, manufacturing, and production process - many products can now be fabricated using AM methods. Iterative design processes require close collaboration of all entities involved from design to production; with AM, the lines between these previously stove-piped steps become blurred. A need to design, test and adopt different maintenance workflow becomes a necessity in cases of preventive and corrective maintenance of mechanical components on Navy ships and aircrafts where such operations have major impact on operational readiness.

This project proposed to study and test elements that are identified as critical for effective deployment of AM in Navy operations, with specific emphasis on maintenance operations, while remaining sensitive to other Navy domains and activities where the use of AM can bring significant value. The overarching goal was to provide a comprehensive approach that would lead towards reduction of energy costs, mitigation of risks, as well as reduction of materials and human resources engaged in that process.

Inspired and aided by the open-source NIH Model Exchange project, this project has developed a model exchange website and backend capabilities to enable secure contribution and sharing of AM models using the latest open source software. Related research work includes partnered efforts by Dr. Dr. Amela Sadagic on diffusion of innovation across the Navy and Marine Corps. This tandem work has guided corresponding implementation of numerous specific aspects in Model Exchange (MX) design with respect to deployment, scalability, access, repeatability, and user value. Continued work appears fully feasible and is expected to provide fundamental long-term value.

Findings and Conclusions

Phase One: Model Exchange Portal Design

Year one of this project (from FY2017 NRP project NPS-17-N244-A) laid the basis for design and initial implementation. Despite personnel challenges, our group has persisted and continued evolving sophisticated work to develop and deliver key capabilities. Such work was essential and has included direct involvement in multiple Extensible 3D (X3D) Graphics Working Groups as part of membership in the Web3D Consortium. The royalty-free Extensible 3D (X3D) Graphics International Standard was shown to have fundamental value by mapping well to diverse commercial formats and by adding integrated features for metadata provenance, visualization, Web viewability, and model composition. X3D Working Groups in the non-profit Web3D Consortium provided continuing further value. Early February 2018 included a well-attended project review at

NPS that reviewed plans and developed detailed strategies. We have followed that collaborative plan closely, to good effect. The findings and conclusions of this project follow the three phases identified there: design, developers beta testing, and soft launch testing as part of current work.

Phase Two: Developer's Beta Testing

The ability to find printable models by category, community, and metadata tags is currently in developer's beta. Presently, GitLab-based automation for processing and preparation is found in the Model Exchange Staging Area (MXSA). Procedures continue to be refined using automated and manually performed processing, resulting in steadily increasing automation capabilities. The GitLab repository supports the X3D Model Exchange portal by hosting developer assets. All contributions are unclassified open source, with either public or For Official Use Only (FOUO) access. Membership is strictly controlled to block hackers and ensure professional progress.

The Model Exchange Staging Area (MXSA) repository serves as a staging area, holding 3D model assets for the X3D Model Exchange. Here, developers can add any assets of interest into a project. These assets include but are not limited to 3D models, data, metadata and videos. Developer participation is by government personnel, or designated contractors in a support role.

ModelExchange7 and ModelExchange8 are two further repositories supporting code and configuration files deployed as part of the X3D Model Exchange portal. Developed using Drupal 8 code and other open-source assets, and extending the Drupal 7 predecessor open-source 3D Print Exchange developed by the National Institutes of Health (NIH), the resulting X3D Model Exchange is online at https://ModelExchange.nps.edu with public-facing support.

Phase Three: Soft Launch Testing and Current Work

Soft launch testing began in summer 2018 by inviting our first Navy and Marine Makers. Early users first verify that they have a 3D model saved to any format and identify the appropriate level of access applicable to the model, i.e. For Official Use Only (FOUO) or unrestricted. The model title, author information and hash tags are then used to upload the model to GitLab's Model Exchange Staging Area. Makers then provide the details in a description of their open source model. These details may include drawings, plans, photos and videos. Uploaded user models are then acknowledged by Model Exchange administrators and then further tested and prepared by partner developers in the Model Exchange Staging Area using NPS GitLab version control. When ready, the new model assets are placed into the Navy X3D Model Exchange and published according to their administrator-confirmed level of access. We are publishing models on a weekly basis.

With the Drupal 8 update complete, 3D model upload/download testing continues. Current work includes providing tutorials for end users who are learning the system, creating FAQs and other help files, development of community forums, and improving the taxonomy of metadata vocabularies. Models are accepted each week with ongoing incremental processing improvements.

Community building and engagement remains a critical component for growing the X3D Model Exchange. The primary resource for Navy and Marine Makers on the Model Exchange site is the community-driven discussion forums. Here, Makers can contribute to various partner forums, site development forums, and share lessons learned on how to make something new. Additionally, the administrators provide reports on Model Exchange site progress to community members. The X3D Model Exchange also maintains a social media presence on both YouTube NavyMakers and Twitter@NavyMakers where highlights and developments within the broader additive manufacturing community can be shared. Weekly teleconferences with Seabee users continue guiding this work, and further activity is expected with Marine Makers. Much continued future work is expected in direct support of NPS Strategic Plan and multiple external partners.

Recommendations for Further Research

This report provides only a small slice of the many activities being integrated and enabled. Interested users are invited to explore the portal to learn much more. Interested developers are welcome to contact us and learn about collaboration opportunities.

- Continue development and maintenance of the Drupal 8 website with shared issue tracking.
- Finish integration Completely Automated Public Turing test to tell Computers and Humans Apart (CAPTCHA) and CAC controls directly into the ModelExchange.nps.edu website.
- Further automate the integration of backups and newly added models & metadata with the NPS GitLab repository and its processing functionality.
- Support multiple maker communities: Navy, Marine, Expeditionary and History/Heritage.
- Collect longitudinal metrics and statistics to measure usage and indicate areas for growth.
- Continue participating in Web3D Consortium X3D Working Groups to extend standards support for 3D printing, scanning and visualization in support of DoD Digital Engineering efforts.
- Share models with Naval Facilities Engineering Command (NAVFAC) SPIDERS3D Virtual Environment, build "sand table" capability.
- Tighten website processing with data-centric security to ensure models remain uncompromised.
- Continue to build community through social media and other means of communication.
- Continue to "tell the story" of developers and users through interviews and video.

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NPS-18-N386-A: Culture Change and Modernizing Navy Logistics

Researcher(s): CDR Sue Higgins USN Ret., Dr. Erik Jansen, and Ms. Ann Gallenson

Student Participation: No students participated in this research project.

Project Summary

This project considers how to accelerate culture change within Navy logistics organizations in step with the continuing modernization efforts. Our findings integrate previous culture change research with updated reviews of literature, discussions with logistics leaders and key stakeholders. Additionally, we are designing the capacity for extending the socialization of modernization concepts through "design sprints" that enable us to gather inputs from a diverse population of key stakeholders and outputs from personnel within the logistics community. The final report includes the capacity designed and the results of early events.

As the Navy Logistics community reforms and modernizes its technologies, processes, and organizations; leaders recognize that change is dependent not on their actions alone but on the organizational culture, which can enhance or impede adoption. Culture arises as a shared understanding of current and future pressures. It changes by adapting to external and internal forces (Schein, 1985). Initially, people often resist change. The Navy's bureaucratic systems are designed for stability, not agility; reliability rather than responsiveness. By increasing the agility of its organizations and leaders, the logistics community will be able to better respond to its customers, naval and joint warfighters, who operate in turbulent environments across a spectrum of combat to humanitarian missions. The ultimate goal is to increase the lethality of naval and joint warfighters.

Keywords: *culture change, learning organizations, innovation, agile organizations, agile leaders, logistics modernization*

Background

The Chief of Naval Operation (CNO)'s Design for Maritime Superiority identifies concerns about accelerating rates of change and highlights the need to reexamine approaches in every aspect of the Navy's operations. Modernizing logistics will reap benefits afloat and ashore. Logistics leaders must align strategy, organizational structures, work practices, training, education, continuous learning, rewards and incentives (Jansen, 2015). Continuous environmental assessment and alignment can reduce cumulative challenges and accelerate the Navy's change successes.

The Navy's Strategic Readiness Review (SRR), published in response to a series of ship collisions, calls for Navy leadership to foster a culture of learning and create structures and processes that fully embrace this commitment. This is consistent with our research about accelerating culture change. Our final report addresses the range of areas leaders could consider.

The agile software movement, in which value is placed on adapting to change as learning occurs instead of adhering to a prescribed plan, is intriguing Navy leaders. However, it is unclear how the practices of agile software development scale and extrapolate to agile organizations as large and complex as the Navy. Researchers have only begun reporting on the lessons of agile scaling from the private sector (Rigby, 2018).

We observe that Navy leaders often use words without clarifying meaning, assuming that their audiences' definitions match their own. Leaders should create shared meaning as they work to change their organizations. Building on previous research, we use the following definitions:

- Culture –"The set of assumptions (often unstated) that the members of a community have in common." (Sathe, 1985);
- Innovation – "The adoption of a new practice in a community." (Denning, 2010) ;
- Agility – "The ability of leaders and organizations to rapidly pivot to new problems and adapt to new circumstances." (Koutstaal, 2012) ;
- Learning organizations – "Exhibit systems thinking (developing awareness of complexity, interdependencies, change and leverage), personal mastery (cultivating individual aspiration and awareness), mental models (becoming more aware of the sources of our thinking), shared vision (fostering commitment to common purpose), team learning (transforming our skills of collective thinking)." (Senge, 2000).

Findings and Conclusions

We provide a series of topics and questions for logistics leaders to consider with their teams as they lead organizations through culture change. The topics include: strategy, structures, processes, rewards and people.

Our Design Thinking (DT) engagements with Supply Corps Officers and stakeholders explore: How the adoption of disruptive technologies such as automation, artificial intelligence, and additive manufacturing impact unit-level readiness? How must Navy communities change to embrace the opportunities offered by these disruptive technologies?

Design workshops provide a way for researchers and leaders to pose provocative questions to a cross section of personnel who actively solve problems inherent to innovation. The Navy's Illuminate Thinkshops are design workshops, supported by Fleet Forces Command that can be leveraged by the logistics community to help to spread the conversation of change to a cross section of personnel within and outside of learning institutions. These workshops and Design Thinking engagements help to socialize change initiatives and fuel them through developing a mindset of action through iterative concept generation, prototyping and testing.

Recommendations for Further Research

- Continue review of ever-growing literature about agile organizations, agile leadership, innovation and learning organizations.
- Revise curriculum at Supply Corps School to include agile organizations, agile leadership, innovation leadership, human centered design.
- Write a case study about the adoption of DoD contracting's "Other Transitional Authority (OTA).

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N8 - Integration of Capabilities & Resources

NPS-18-N263-A: Optimal Payload for Multi-Mission Unmanned Systems

Researcher(s): Dr. Moshe Kress, and Dr. Michael Atkinson

Student Participation: ENS Stephen Ward USN

Project Summary

The Tern is a future Navy unmanned aerial system (UAS) that will deploy on and launch from surface ships such as destroyers. It is designed to be capable of performing multiple types of sorties such as anti-submarine warfare (ASW), information, surveillance, and reconnaissance (ISR), and acting as a node in a communication network. Each type of sortie has different operational and physical requirements manifested in the payload onboard the Tern. There are two forms a payload can take: fixed and modular. The fixed payload is hard-wired into the Tern while the modular payload space on the Tern supports the ability to change the payloads for each sortie. Multiple possible scenarios and operational postures add another level of complexity in determining optimal payload configurations. The overarching issue that we address in this research is the general design of the Tern payload. This design must take into account the inherent stochasticity of the situations

in which the Tern will operate. While conducting a primary task within a sortie, the Tern could also be called to carry out other tasks as the situation dictates. For every possible realization of a sortie a Tern is sent on, there is an optimal payload design that addresses the possible tasks in the sortie. Consequently, each design satisfies a given measure of effectiveness (MOE) with a certain expected effectiveness. The objective is to find a global payload design that maximizes responsiveness over all possible sorties and scenarios.

Keywords: *unmanned systems, knapsack problem, packing problem, integer programming*

Background

The use of unmanned aerial systems (UAS) has been growing in recent years within the U.S. military, and its implementation brings a wide array of benefits to the Navy in particular. There exist many beneficial attributes of these unmanned aircraft in their reduced cost, increased endurance, limited need for training, ability to send into high-risk situations, and more. These systems are only being used more, and thus there lies a need to analyze and optimize their potential.

The Tern is an upcoming UAS which will be used to supplement the resources available to surface action groups (SAGs). The Tern has an advantage in its ability to vertically take off and land, consequently not requiring more than a helicopter launch pad on its home ship. Once it is airborne, the Tern can shift to flying horizontally with its fixed wing structure. The Tern is also capable of being stored in a compact manner, allowing for multiple Terns on each ship.

The problem this project investigates is the configuration of payloads onboard the UAS. A *payload* is an item which may be considered for attachment on the Tern. Payloads range from weapons to sensors and communication devices. A *sortie* is the specific mission the Tern is sent to conduct. Over the course of a deployment, the UAS is expected to conduct multiple unique sorties. Since certain payloads may only serve a purpose for some of the sorties, but not all, we consider attaching them as either fixed or modular. If such a payload is fixed, then that payload and all of its mechanisms will be attached in a particular slot for every sortie the Tern undergoes - including those sorties for which it is unneeded. If a payload is modular, then it can be attached and detached as needed according to the planned sortie and its associated tasks.

From a purely functional aspect, it would obviously be ideal for all payloads to be modular so as to maximize tactical flexibility. However, physical constraints such as weight, volume, time to prepare and other factors must be considered when evaluating the trade-offs between choosing modularity versus fixed installation. For example, a fixed payload is presumed to take up less space and be more robust to failure than a modular design which may require additional parts and attachments.

Many studies have been performed in recent years on the use of UAS. Payton (2011) analyzes the best application of UAS for the Marine Expeditionary Units (MEU) with an array of possible sorties. The knapsack problem, which is at the core of our optimization model, is one of the most commonly known problems where there exists a container with a finite capacity and several items with associated weights and values. The goal is thus to achieve the highest value of the items in the container without exceeding its capacity (Fréville, 2004). The problem we are studying is more than just that of the knapsack where only one container is present. Rather, there are multiple bins with varying characteristics which we refer to as slots. This structure is akin to the multi-dimensional bin packing problem (MD-BPP) where the goal is to fit all the objects demanded into a set of allotted bins (Martins, 2003). Further studies show the use of MD-BPP applied to the packing of boxes into containers on a cargo airplane (Paquay et al., 2016). We have extended the model to include the idea of sorties where the Tern in our case must be re-packed with modular payloads before each launch. From reviewing similar previously studied problems, it appears that our approach is unique in our focus on the decision of making payloads fixed or modular. We claim in our research that the use of modularity within situational and physical constraints leads to far better solutions to meet the challenges faced on deployment.

Findings and Conclusions

The basic mathematical approach we take in this research is based on the classical knapsack formulation (Kelly et al. 2003). Essentially, we would like the Tern to be loaded with as many of the best payloads for the tasks of each particular sortie while maintaining feasibility regarding weight, volume, vibration, and other constraining factors. The goals for our model can be simplified to:

1. Goal 1: Choose a configuration of payloads to maximize performance potential across several different sorties, each of which conducts multiple tasks
2. Goal 2: Choose a configuration of payloads that utilizes as many fixed payloads as possible to effectively execute sorties.

We start with a simplified formulation to demonstrate the modeling approach for capturing Goal 2 in the presence of the uncertainties regarding sorties and tasks. To do this, we seek to maximize the number of fixed payloads used to meet sortie requirements. This promotes robustness in the sense that we reasonably assume fixed payloads are less likely to fail as well as require less preparation time before a sortie. Ideally, the best payloads could all be fixed, but this is rarely achievable. This simple model serves to highlight the trade-off between robustness and flexibility. The simple model is not trivial. We propose a greedy algorithm to solve the simple model that works well in many cases but is not necessarily optimal.

The full model has an objective which seeks to maximize the expected performance potential of the Tern for a deployment (Goal 1) while adhering to physical limitations. The goal of the optimization model is to find the optimal balance between fixed and modular payloads such that the Tern is best equipped for every possible sortie. This approach tends to result in configurations with more modular payloads in order to achieve greater tactical flexibility. The majority of the constraints within our model are physical limitations with respect to the payloads, slots, the Tern as a whole, and even the ship itself. We assume that since the Tern is designed for use on smaller Navy vessels such as a destroyer, there will be limited space to store payloads.

Both the simple model and full model are zero-one linear programs where the decision variables are centered on the payloads. The model decides whether a payload will be fixed or modular. If it is fixed, it chooses where on the Tern it is fixed. If it is modular, then the model decides for which sorties it is placed and where. The model is implemented in Pyomo and solved using the CPLEX solver.

The purpose of this project is to provide a tool which can be used to better understand the intricacies of fitting a diverse set of objects in spaces with many physical limitations which must adhere also to the constraining factors of the system as a whole and meet a variety of demands.

We run through several numerical examples of increasing complexity to illustrate the effectiveness of our model. We include many different payloads, sorties, and tasks. We find in this research that the solutions produced by our model are sensible, but not simple. The results favor fixed payloads when possible while still striving for the best total value through the use of modular design. Often, we see results where the model makes trade-offs between various payloads that would take a great deal of analysis and enumeration by hand to arrive at the same solution.

We also provide an example of extending the application past a single configuration of the Tern to two and three unique models. By doing this, we find a method to increase the proportion of fixed payloads for any one Tern and possibly increase its effectiveness.

Finally, we study the effects caused by perturbing several data parameters in the input. We conclude that variations can sometimes cause significant drops in the objective value due to infeasibilities, but high levels of success are more often achieved.

Recommendations for Further Research

There are several opportunities for continuing research on both the formulation and application of our model. It would be beneficial to construct and analyze different objective functions for our optimization model with respect to performance. Our formulation defines a value between zero and one for each payload applied to each task. This generates an expected value metric for our objective function similar to utility in decision theory. There is potential for the objective value to be defined by other metrics. One example is to maximize the area of the distribution of the SAG. Another option is to penalize the objective value for creating a configuration which depends on beyond line of sight communication. Furthermore, the current objective value does not account for potential synergies created among multiple payloads.

Further work could study the consequences of integrating the Tern with a ship. One must consider the need for spare parts, training sailors to maintain and repair the Tern, and if the Tern will increase the warfighting capability of the ship by replacing the helicopter(s) currently in use.

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NPS-18-N338-A: Optimal Mission Planning for MCM Vehicles and Sensors

Researcher(s): Dr. Isaac Kaminer, Dr. Sean Kragelund, and Dr. Claire Walton
Student Participation: No students participated in this research project.

Project Summary

Mine countermeasures (MCM) is an extremely challenging and complex Navy mission, due to the wide variety of potential threats and operational environments encountered. Unmanned vehicles and advanced sensors play an increasingly integral role in these missions, but MCM commanders and vehicle operators still lack an ability to maximize the utility of these new search assets. Recent research at the Naval Postgraduate School (NPS) has produced a computational framework for solving optimal search problems with realistic sensor models, nonlinear vehicle dynamics, and parameter uncertainty. This motion planning framework has been used to optimize mine hunting trajectories for unmanned vehicles conducting MCM missions. This project investigated ways to include environmental factors and image quality considerations into the planning framework. The initial goal of this research was aimed at reducing the amount of unusable imagery collected during sonar surveys, since post-mission analysis (PMA) by human operators is one of the main

bottlenecks in the MCM detect-to-engage sequence. A review of the literature, however, suggests that automatic target recognition (ATR) and data processing capabilities onboard search vehicles have an even greater potential to improve mine clearance rates. As a result, this project also examined the computational feasibility of executing NPS optimal motion planning algorithms directly onboard unmanned vehicles, a key enabler for collaborative MCM operations.

Keywords: *optimal control, optimal search, mine countermeasures, motion planning, autonomous vehicles, unmanned vehicles, unmanned surface vessel, autonomous underwater vehicle, sonar, detection models, mission planning*

Background

The ocean environment plays a major role in sonar performance. When searching for mine-like objects (MLOs) on the seafloor, bottom composition, roughness, clutter density, and burial potential are important factors (Dubsky, 2000), especially since modern sonars generate high-resolution imagery and targets must be detected against different backgrounds in the image domain. This is usually accomplished through a laborious PMA process, performed manually by human operators, or increasingly, by ATR algorithms. Recently, onboard sonar processing identified (ATR) as one of the most important characteristics impacting future MCM system performance (Camacho et al., 2017). Simulation is a powerful tool for comparing sonar performance in different environments (Dubsky, 2000; Percival & Stoddard, 2010). More recently, it has also been used to generate synthetic imagery (DeMarco, West, & Howard, 2015; Gwon et al., 2017, p.; Pailhas, Petillot, Capus, & Brown, 2009; Saç, LenlebicioğLu, & BozdağI Akar, 2015) to train and evaluate the detection performance of both human operators and new ATR algorithms (Groen, Coiras, Vera, & Evans, 2010; Mignotte, Vazquez, Wood, & Reed, 2009; Reed, Petilot, & Bell, 2003).

Sonar surveys are often complicated by environmental conditions which vary significantly over the desired search area, and several image-based segmentation approaches have been proposed to address this mission–planning challenge. Algorithms have been developed to estimate areas with different seabed types based on sonar imagery (Reed et al., 2003; Williams, 2009, 2010a). This information can help identify favorable areas for conducting MCM and establishing Q-routes (Dubsky, 2000). It can also be used to partition a mission area into sub-regions based on expected sonar performance (Hyland & Smith, 2015), assign areas of responsibility to differently-equipped search vehicles (Costa & Wettergren, 2010), and provide recommended track-spacing for lawnmower survey patterns based on the bottom type of each sub-region (Johannsson, Thorhallsson, & Hafsteinsson, 2006; Wiig, Krogstad, & Midtgaard, 2012; Williams, 2009, 2010a, 2010b).

The optimal motion planning framework described in (S. Kragelund, Walton, & Kaminer, 2016) and (S. P. Kragelund, 2017) developed signal excess target detection models for MCM vehicles and sonars, but also made several simplifying assumptions about the environment and seafloor. One goal of this research was to assess whether image-based detection models and environmental information can be used to generate optimal motion plans that produce better sonar imagery, reducing the amount of PMA required.

Findings and Conclusions

This investigation determined that our model-based framework can accommodate existing high-fidelity sonar performance models such as the Navy's Comprehensive Acoustic System Simulation (CASS), although the additional computation required does not support rapid re-planning within a trajectory optimization routine. Moreover, developing new environmental models for this purpose was beyond the scope of this project. Similarly, we investigated several techniques for simulating and/or predicting image quality based on the type of seabed.

Nearly all of these methods divide the mission area into sub-regions for coverage by a conventional lawnmower search pattern whose lane spacing is determined by expected sonar performance for a given range and bottom type. They do not address image quality directly, but assume that their prescribed lane spacing will produce images of sufficient quality to allow detection by PMA or ATR. In this way, these planning methods aim to improve area coverage rates and reduce the percentage of missed targets. These assumptions are reasonable for the straight and level mission profiles required for side scan or synthetic aperture sonar (SAS), but may be overly conservative for vehicles equipped with forward looking sonar systems that have fewer motion constraints.

Secondly, all search problems must balance the probability of successful target detections against the probability of generating false alarms, a decision usually made at the sensor design stage or mission planning stage. This uncertainty drives the need for additional sorties to confirm whether or not previously detected contacts are indeed mines. Some methods for performing contact investigation with the same vehicle used for initial target detection have been proposed (Johannsson, et al., 2006 and Wiig, et al., 2012). Potentially greater clearance rates can be realized when contact investigation sorties are conducted in parallel with detection surveys, however this capability requires sufficiently fast onboard motion planning algorithms to respond to new target detections.

After presenting and discussing these initial results with the topic sponsor, we began examining the feasibility of an optimal motion planning framework onboard MCM vehicles, assuming typical open source software and computer resources. The numerical optimization performance of different algorithms was compared for several known test problems provided by (Schittkowski, 2008). A laptop computer with Intel Core i7 processor served as the benchmark computing configuration. Test configurations included an ODROID XU4 and Nvidia Jetson TX2. All three configurations utilized the Ubuntu 16.04 Linux operating system. Several sequential quadratic programming (SQP) optimization algorithms were tested, including MATLAB's fmincon, various open source Python libraries (e.g., SciPy's SLSQP), and MATLAB/Python interfaces to the well-known Sparse Nonlinear OPTimizer (SNOPT) (Gill, Murray, & Saunders, 2005). Our comparison revealed that Python optimization libraries could solve a standard optimal control problem ten times faster than MATLAB's fmincon on the laptop, and two times faster than MATLAB on the ODROID. These preliminary results indicate that our optimal motion planning framework is feasible—even when using typical computer resources onboard MCM vehicles.

Recommendations for Further Research

Teams of heterogeneous vehicles with complementary capabilities have potential to significantly improve MCM clearance rates, but only if they can overcome the limitations of the prevailing sequential search paradigm. Fortunately, researchers have made steady progress toward useful ATR algorithms, a key capability for reducing the laborious PMA required between vehicle sorties. Assuming that improved sensors and machine learning techniques will soon make ATR a practical reality, mission planning is another bottleneck in the MCM timeline that must be addressed. To contribute toward an autonomous, detect-to-engage capability, future research should investigate motion planning techniques which can utilize appropriate vehicles and sensors to classify detected objects as needed. This will likely require new methods for updating underlying target probability models based on individual vehicles' mission progress, and fast optimization routines suitable for in-stride re-planning in response to new information.

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NPS-18-N124-C: Aqua-Quad - Hybrid Mobility and Sensing in Support of Collaborative Undersurface Warfare

Researcher(s): Dr. Vladimir Dobrokhodov, Dr. Kevin Jones, Dr. Paul Leary, and Dr. Kevin Smith
Student Participation: LT Joseph Testa USN

Project Summary
The project builds an experimental model as a proof of concept of a novel anti-submarine warfare (ASW) platform, AquaQuad. The envisioned vehicle is a hybrid, including features and capabilities of an energy independent drifting sonobuoy and a multirotor vertical take-off and landing unmanned aerial vehicle (UAV). As such, AquaQuad integrates a multicopter UAV with a tethered acoustic sensor, environmentally hardened electronics, communication links, and a solar recharge system. As a single system the AquaQuad design is easily scalable which enables its modification to different sensor modalities, weight of payload, communication, and energy harvesting requirements. In turn, multiple cooperative AquaQuads are designed as hybrid-mobile, collaborative platforms that ride on ocean currents and fly over significant distances when required by the mission. Flight is triggered to enable rapid repositioning for submarine tracking with lower dilution of precision (DOP), collision avoidance, and communication with neighboring vehicles. Overall, the distributed swarm of energy independent and autonomous AquaQuads represents an information harvesting and communication system that, depending on the specific objectives, can be focused on various naval and civil applications.

To date the project has identified the mathematical models of key subsystems of the AquaQuad in the major modes of operation. They include two distributed (over depth) components - the surface and submerged units, connected via a tether, which operate autonomously in passive search while in energy harvesting drift and in energy bursting flight modes; a number of sub-modes is envisioned/included to address the specific nature of silent operation under strict communication and energy constraints. An experimental setup of the surface unit and the submerged data acquisition (DAQ) system has been built. Operational capabilities of separate components are verified in controlled laboratory experiments. System identification experiment has been performed to identify the maximum achievable capabilities of the ARM-based data acquisition system and the potential bottlenecks of the envisioned information processing architecture. The power distribution and communication subsystem has been conceptualized and prototyped in hardware to enable practical evaluation of the power transmission and data exchange bandwidth over a dual wire tether. The corresponding communication mechanism (hardware and the communication protocol) is outlined to enable embedded microcontroller implementation. The long haul and local wireless communication are adopting the existing Iridium and 802.11x solutions where the bandwidth available drives the underlying decision making and data preprocessing tasks.

Keywords: *underwater acoustics, energy harvesting, acoustic sampling, DFFT, embedded system, beam forming, acoustic target motion tracking, path planning, UAV, flight control*

Background
The Persistent Littoral Surveillance Network (PLUSNet) (Steward & Pavlos, 2006; Benjamin, Schmidt, Newman, & Leonard, 2010) is a concept for cooperative ASW that is considered in the current project as the most Navy relevant design-defining framework. The key objective of PLUSNet is to enable cooperative persistent detection, classification, localization and tracking (DCLT)

capabilities with significant onboard autonomous decision-making. The PLUSNet concept addresses a broad range of technologies (Scott, 2007) that include the platform design, power, persistent autonomy, communication, mobility, navigation, signal processing, acoustic wave propagation, network level tracking and response, environmentally adaptive sensing, and networked control. Despite the significant advances made in the development of ASW technologies (Scott, 2007; Martin, 2005), the most significant gaps still exist in the areas of responsive mobility and timely communication of acquired contacts; in short, it takes too long to communicate the positively identified signatures to either the cooperative vehicles and/or remote data processing centers to guarantee correct classification of potential threats. Low bandwidth and operational range of communication links, and low mobility of the undersurface autonomous platforms within the existing onboard energy budgets, are the key constraining factors of the current state of the art of ASW technology.

Motivation for a new approach. On the ocean surface, buoys and disposable floaters are frequently used, but are subject to ocean currents, providing mobility, but not (Steward & Pavlos, 2006) mobility in the desired direction. They typically provide limited sensing at or near the surface, and are usually limited to low-bandwidth satellite communications or data storage until they are retrieved; in the latter case this typically results in the need to deploy another manned aircraft to perform a data acquisition mission. Underwater there are few solutions. For example, sea gliders (Martin, 2005) provide long endurance and at least some mobility beyond ocean currents. However, they are limited to undersea and surface sensing, and are typically out of communications most of the time, again limited to low-bandwidth communications when they are on the surface. Wide area, long endurance coverage in the air over the ocean is also challenging. One ongoing study, TaLEUAS (Camacho, Dobrokhodov, & Jones, August 24-29, 2014), proposes to utilize a flock of networked airborne gliders that use a combination of natural, convective lift in the environment and photovoltaic cells coupled to high specific energy rechargeable batteries to provide 24/7 aerial coverage. While this concept is promising for aerial missions, intelligence, surveillance, and reconnaissance (ISR), communications-relay, etc., it is not of much use for sensing at the ocean surface, underwater, or ground sensing where severe proximity limitations exist, such as looking for mines buried in the beach. None of these schemes are able to cover all environments, air/sea/ground, and each includes constraints for communications, mobility, and/or survivability in harsh weather.

The AquaQuad is a true hybrid platform (Jones & Dobrokhodov, 2014), capable of use in all these environments, with both air and surface mobility, 24/7 sensing and high bandwidth communications. The multicopter-based AquaQuad uses a mix of floating and flight segments, and through the use of modern high efficiency solar cells and high specific-energy rechargeable Lithium batteries, the mission endurance for the vehicle can be extended indefinitely, flying when necessary, but floating and riding ocean currents most of the time while performing sensing tasks with minimal power consumption.

Envisioned concept of operation. There are many possible mission scenarios and sensory capabilities that would be of interest for both DoD and non-DoD applications. However, the present work focuses on the use of passive acoustic vector sensors, deployed to a depth below the thermal layer, and used by a flock of AquaQuads to collaboratively detect and estimate the position and motion of underwater targets. In the envisioned concept of operation, a "flock" of Aqua-Quads is outfitted with deployable, passive acoustic/magnetic sensors, and distributed in a grid over the sea surface to search for undersea objects of interest. The first vehicle that picks up a signal and collects a sufficiently rich sample might pop up high enough to form a network with nearby AquaQuads to announce its detection and to enable cooperative target motion estimation (distance/bearing only, time difference of arrival (TDOA), etc.), or to relay the information to nearby manned or unmanned surface or airborne assets including the communication of data over a satellite link.

Technical Approach and the Key Findings

The project is highly interdisciplinary. Therefore, it naturally includes a number of tasks from several adjacent engineering disciplines. As such, one of the most academically challenging tasks is to develop a systematic engineering approach to enable functional integration of multiple state of the art solutions from those disciplines. For simplicity they are divided into hardware and software tasks focused on the surface and the underwater components of the AquaQuad, therefore giving us 4 distinct research and development (R&D) directions to pursue. During the two years of research the focus areas included optimization of the avionics, propulsion system, and airframe, development of design tools required to optimize the enclosures (surface and the deep water vessels) to provide up-right floating stability along with a self-righting capability, and the development of a data-acquisition system and embedded software for the proposed acoustic payload and the surface processing unit. The tasks of the tether design (that connects the surface and the submerged acoustic units with power and data) and the long-distance command and control (C2) communication are the latest research directions that we recently addressed.

On the hardware design side, the team has explored various design options for onboard autopilots that rapidly evolve, thus featuring more compact and higher performing hardware, software, and communication components. In particular, the project migrated from the PixHawk autopilot to the new, much smaller PixRacer, which costs less, weighs less, and has increased compute power, a higher precision and robust Inertial Measurement Units (IMU), and a Global Positioning System (GPS) unit capable of picking up 4 satellite constellations for improved precision and reliability.

Other work on the hardware front has focused on the design of the exoskeleton, in particular, the structural support for the solar array. The previous model utilized a structure cut from pre-fabricated Carbon fiber/foam sandwich panels that were about 7mm thick. That design has worked fine for initial test flights on dry land, and while we have performed flotation/stability tests with it on the bay without mishap, we are concerned that it will fail on hard landings or in rougher seas with breaking waves. Additionally, it is somewhat challenging to distribute buoyancy as required to meet stability requirements and support a self-righting process. We are currently working with a composites vendor to manufacture a foam-core composite structure optimized for the task.

In the early prototype of the single AquaQuad vehicle, one of the central frame plates was a printed circuit board (PCB) that included sensors for tracking power flow from solar to batteries and electronics. This plate has now been replaced with a much smaller PCB that includes a DAQ system along with power regulation for avionics and payloads, and the frame plate was replaced with a stronger, lighter Carbon fiber plate. The DAQ is an off-the shelf, very low Size Weight and Power (SWAP) device that is based on an ARM microcontroller that retails for about $30. Components from the rapidly evolving drone-race market are being investigated as replacements for some of the propulsion system - in particular, the electronic speed controls (ESCs). Newer options are smaller, lighter, and more efficient.

Software of the surface processing unit includes a number of tasks such as analog and digital signal acquisition, preprocessing, identification of acoustic signature, energy management, global and local path planning, local and long distance communication, and high-level decision making tasks to name a few.

All of those tasks are the integral parts of the soft-real time information flow process that is to be implemented within the client-server architecture conveniently provided by the Robot Operating System operating system (ROS). While ROS is considered as a well-established framework for the implementation of distributed processes, it is also recognized as merely a prototype software environment which, if necessary, can be easily changed to a more specific solution; MOOSE, SPREAD (and many others) are similar candidates for implementation with their own pros and cons. However, ROS is well-supported by the robotics community and provides rich support of standard commercial off-the-shelf (COTS) components like wireless communication links, sensors, actuators, and communication protocols.

Path planning is one of the most computationally intensive tasks of the surface unit. The task is to find the energy-optimal trajectory for the AquaQuad in transition from one point to another within the given constraints of energy available onboard. The computational load required was evaluated in our previous work (Dillard, 2014) that relied on fundamental ideas of space sampling by rapidly exploring random tree (RRT)* algorithm. Some operational deficiencies of the original RRT* were addressed by modifying its logic and designing the energy-relevant cost metric that allowed significant increase in speed of calculations. However, the central processing unit (CPU) load was verified to be the heaviest among the other envisioned tasks to be performed by the surface processing unit. To address the complexity of verifying the 'closeness' of a feasible path to the optimal solution given by RRT* modification in (Dillard, 2014), we address the problem of energy efficient path planning by utilizing a different class of methods – a boundary value problem. The energy optimal path planning is now formulated as a two-point boundary value problem with the cost function reflecting the energy required. The vehicle is modelled as a point mass dynamic system that has solar energy capture capability. The vehicle moves in a vector field that represents known ocean currents; if the currents are not know a separate task evaluates them in a parallel process. The limit of the available energy is natively bounded by the energy capacity of the onboard batteries. The objective of the optimizer is to find the minimum energy path within the time-varying field of currents and possibly stationary obstacles. The task is first solved semi-analytically in MatLab and then transitioned to the embedded Python process running in the ROS as an action-server task. The computational load of the solution was specifically addressed. While the first version of the task took nearly 8 hours on a typical Core-i7 based desktop, the latest release running on the target CPU Odroid takes about 1 minute for the same computation.

On the submerged acoustic sensing side, work has been performed in collaboration with researchers in the NPS Physics department and at Naval Undersea Warfare Center (NUWC) Keyport. The envisioned payload is an acoustic vector sensor (VS-301 by Wilcoxon (Wilcoxon Sensing Technologies, n.d.)) which hangs on a thin 2-wire tether from the bottom of AquaQuad to sense at a suitable depth. Processing of this acoustic data yields an estimate of bearing to source (beam forming). The sensor produces a mix of high bandwidth analog (acoustic signal) and digital (attitude) outputs that go through a data acquisition phase, and then run through post-processing filters to attenuate noise, identify the signals of interest, perform coordinate transformation and beam forming, and reduce the data to a manageable quantity for transmission via tether to the surface level. The DAQ currently being developed (Teensy 3.6 by (PJRC)) is based on 32-bit 180 MHz ARM Cortex-M4 processor with floating point unit. It has sufficient compute power to enable concurrent analog to digital conversion (ADC) of multiple analog channels as well as data processing - all running in multithreading mode. The latest developments integrated both the acoustic data sampling, coordinate transformation, and the beam forming algorithms (intensity processing) within the Cortex-M4 CPU.

Software development included the design of information flow architecture of the surface and the submerged acoustic units. The objective of the acoustic unit is to process data of the VS sensor in hard real-time; the unit is built around the VS-301 sensor and ARM-based microcontroller that reads its data. While the wide band acoustic data is sampled and processed in hard real-time, the resulting output will ultimately contain only low bandwidth 'derivative' information (beam direction in inertial coordinate frame) suitable for communication over long tether to the surface C2 platform. That is, all processing, currently including fast Fourier transform (FFT) processing discrete fast Fourier transform (DFFT version), and the beam-forming operations in the future, is done onboard the DAQ, in order to send only the data necessary for target motion tracking and operational decision making to the surface vehicle.

In addition, a detailed control architecture is currently implemented which allows the surface vehicle to control the DAQ sampling protocol, altering sampling rates and other processing parameters depending on current operational tasks and signals of interest. The architecture implements a 'language' of communication between the surface control unit and the underwater DAQ capable to follow the high-level commands. For example, the control structure currently allows for broadband acoustic monitoring, but if a target or other feature is identified in a specific range, the DAQ may be commanded to alter sampling rates and resolutions to allow high resolution data in a narrow band of interest. The software is written in low-level embedded C language running at CPU clock (180 MHz) with no OS overhead. In turn, the surface C2 unit is based on a much higher level computational platform – Odroid C2 that supports most of the services of conventional desktop; and yet it is tiny and ultra-low power. The software architecture here is based on the ROS operating system running in Ubuntu Linux.

Software development for the DAQ component and the experimental evaluation have shown that the ARM microcontroller and the embedded software can reliably and accurately identify known signals at known bearings comprised of multiple frequencies in the frequency range starting as low as 20Hz.

Concurrent sampling of analog data that is supported by the ARM Cortex board does not introduce any significant computational load. Spectral processing of acoustic data is implemented by highly optimized libraries at the CPU level; computational load due to the discrete FFT (DFFT) is the smallest among several other loads considered at the verification step. Detailed description in the following sections explicitly illustrates the sufficient performance of DFFT processing on the ARM Cortex-M4 embedded platform in comparison with the DFFT algorithm running in MatLab (The MathWorks, Inc., 2017) in computationally unrestricted Core-i7 Intel CPU.

Findings and Conclusions

Major Accomplishments to date include the following:

- Identified mathematical models of key subsystems of the AquaQuad in the major modes of operation:
    - flight dynamics of a multicopter with slung payload
    - flotation dynamics of AQ on the surface with stability margins of self-righting capability
    - energy harvesting and storage
    - major data processing models including the acoustic data sampling and spectral processing
- Built an experimental prototype of the surface unit and the submerged DAQ system. Operational capabilities of separate components are verified in controlled experiments:
    - AquaQuad prototype has been tested in open waters of Monterey Bay.
    - ARM-based DAQ and signal detection embedded software has been tested in the lab.
    - Efficient bearing estimation algorithms have been tested, and are accurate in controlled environment.
- System identification experiment has been performed to identify maximum capabilities of the ARM-based DAQ system and the potential bottlenecks of the envisioned architecture. Identified issues have been analyzed with the proposed solutions in the areas of custom tether design and the software modifications.
- Performed integration of major components for two separate proof of concept experiments:
    - Read multiple harmonics signals and identified the single known signature of interest, and communicated reduced data response to the surface unit for further analysis and communication outdoor flotation test of the AquaQuad surface unit with SWAP characteristics analogous to the envisioned design.

Recommendations for Further Research

The research results obtained to date serve two major purposes – they confirm the feasibility of implementation of chosen architecture, and they frame the scope of additional tasks that can be performed within the architecture. The following is a highlight of specific ideas to be evaluated in the following research steps.

In particular, the results confirm the feasibility of implementation of a hybrid energy harvesting platform in the tasks typical for ASW missions. Both the energy harvested onboard and utilized by the vehicle in drifting mode are sufficient to power the onboard distributed instrumentation and to enable short term flying mode that provides the "mobility on demand" feature of the AquaQuad. On the other hand, the processing performance of the ARM Cortex M-4 CPU and the ADC sampling resolution are more than sufficient to implement the acoustic sampling and the spectral processing of the multiple concurrent signals in hard real-time.

Second, the separation of all the computational loads between the surface and the underwater parts of the AquaQuad needs to be accurately balanced. An adequate implementation mechanism needs to be found to execute the multiple tasks (analog sampling, digital IO, coordinate transformation, communication of data, etc.) within a CPU that is devoid an operating system. On one hand an architecture that does not have an OS provides no OS overhead that tremendously improves computational performance. On the other hand, managing multiple tasks becomes a delicate task to handle.

While we already identified and prototyped in software a number of solutions to the above task of "balancing" computing load, we still need to complete a few tasks in the underwater segment; the acquisition of the attitude data from the digital Input/output (IO) channels, calculation of the beam forming solution, and the communication of processed data to the "surface". Each of those tasks will introduce an additional load to the currently revealed CPU load. There is no problem in accommodating more load in the current architecture; the problem is in designing the computational flow so that if necessary it can be easily transitioned to a more powerful CPU without significant modification. This in fact guarantees the scalability of the data processing. What we want to preserve is the ability of distributed DAQ to be interactive over long distances; short commands to readjust the acoustic sampling to the specific frequency range should not result in hanging the computational flow of the AquaQuad.

As per the software architecture of the surface segment, it is based on key advances of the ROS operating system. Flexibility of the ROS architecture allows adding software tasks (clients, servers, services) at any time. While some of the future tasks are not identified we aim to integrating the core minimum of tasks sufficient with the key functionalities of the AquaQuad. To accomplish that, we need to integrate there the power management and distribution (PMAD) service, the weather (currents and wind) estimation service, and the local and long-haul communication clients.

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NPS-18-N124-D: Sensor Fusion for Undersea Operations

Researcher(s): Dr. Roberto Szechtman, and Dr. Ruriko Yoshida
Student Participation: Capt Ezra Akin USMC

Project Summary

This executive summary describes our results on the research project entitled "Sensor Fusion for Undersea Operations." The first part deals with efficient search with incomplete information, and is motivated by the problem of searching for objects over a large area. In the undersea domain, the goal is to learn the pattern of intrusions so as to efficiently allocate search resources. The model is complicated by the fact that intruders disappear if they are not detected within some window of time. Hence, the more cells the searcher opts to search, the less effective his search can be in any one area. The key operational question we wish to answer is: How should the perimeter be searched in order to maximize the expected number of events intruders over a finite time horizon?

The second part of this project is motivated by the difficulty of wireless sensor networks (WSNs) to provide coverage under water. Due to difficulties in transitioning from WSNs to underwater sensor networks (UWSNs), it is critical to develop fast and accurate communication methods with sensors on the harsh environment of the oceans. In this work, we provide a comprehensive framework to study various approximation techniques in solving discrete-domain optimal sensor placement problems. We consider two general sensor placement problems and adapt some of the most commonly used approximation techniques in solving them.

Keywords: *sensor fusion, undersea operations, multi-armed bandit, MCMC*

Background

In the first part of this project we model and derive solution methods for a family of sequential decision problems motivated by multi-searcher perimeter surveillance scenarios with incomplete information. Namely, we consider the problem of adaptively assigning multiple searchers to cells along a perimeter in order to detect the maximum number of intrusion events. The challenge at the heart of this problem is to correctly balance exploration and exploitation, in the face of initial ignorance as to the arrival process of events. We formulate our sequential decision problem as a combinatorial multi-armed bandit with Poisson rewards and a novel filtered feedback mechanism. To design quality policies for this problem we first derive an efficient solution method to the full information problem (IP). This IP forms the backbone of all policies for the sequential problem, as it allows us to quickly identify an optimal solution given some estimate of the arrival process' rate parameters. We consider the sequential problem in two informational scenarios - firstly where the probability of detecting events is known, and secondly where these probabilities are unknown but one knows how they scale as the number of cells searched increases. For both of these cases we propose an upper confidence bound approach, and derive lower bounds on the regret of all uniformly good algorithms under this our new feedback mechanism, and upper bounds on the regret of our proposed approach.

Regarding the second problem, while the original WSN problem was formulated in the continuous 2-D or 3-D spaces, most recent approaches consider the problem entirely in discrete domain. Instead of optimizing continuous functions using calculus of variation, discrete-domain approaches quantize the search space into finitely many “candidate”' positions and search for the best configurations that optimize a given cost function. This strategy naturally leads to combinatorial problems with the camera, environment, and traffic models encoded in different integral constraints and objective functions. Efforts have been made to formulate the discrete sensor placement problems using standard binary linear programming. While both formulations result in NP (non-deterministic polynomial-time)-hard problems, a myriad of practical solutions including Binary Integer Programming solvers (BIP), greedy approach, greedy heuristics, Monte Carlo simulations and semi-definite programming (SDP) relaxations have been proposed. In this project, we have present and compare strengths and weaknesses of various well-known optimization frameworks to solve the generic sensor placement problem including a greedy approach, Markov chain Monte Carlo (MCMC) methods, and linear programming (LP) and SDP relaxations. By extensive simulations we show that a greedy approach and its heuristic variations are suitable to get the first estimation of the problem. MCMC methods such as Metropolis sampling and simulated annealing are shown to be effective to solve problems with more complicated constrains and large number of variables. On the other hand, the LP and SDP relaxations not only give good approximations of the solutions, but also provide good performance bounds.

Findings and Conclusions

For the search problem, we note the performance of Thompson Sampling is much more variable than that of Combinatorial-upper confidence bound (UCB), as shown through the lower and upper quantiles of scaled regret. This arises due to the potential for the Gamma conjugate prior to be dominated by a small number of observations and create a scenario where Thompson Sampling behaves similarly to a greedy policy - sometimes fixing on good actions, but sometimes on poor ones. The reduced variability and theoretical guarantees of our {FP-CUCB} method make it a more reliable option for real surveillance operations.

Next, we present the key findings for the WSN placement problem. (1) When the number of cameras is sufficiently large, the greedy algorithm has good approximation of IP solution with a fraction of the running time. However, when the number of cameras is small, the greedy algorithm provides much worse results due to its complete overlook of the combinatorial characteristics of the problem; (2) the sampling techniques can trade off performance with computational time; (3) using elements sampled from densities derived from the objective function significantly outperforms those from uniform random sampling; and (4) the greedy heuristics generally out-performs other approximation methods. However, it can still be trapped in a local optimum regardless of the sample size. In a complex environment the sample size will be penalized and cause a disparate disadvantage.

Recommendations for Further Research
The search problem can be extended to adversarial and continuous settings. Regarding the WSN problem, the algorithms can be combined together for solving the generic WSN placement problem even more effectively.

NPS-18-N124-E: Undersea Sensing

Researcher(s): Mr. John Green, Ms. Bonnie Johnson, and Dr. Arkady Godin
Student Participation: CDR Leonard Bunch USN, Michelle Bones, LT Kenneth Fisher USN, Stephanie Mara, and LT Alex Stone USN

Project Summary
The primary goal of the research was to develop a reference architecture for undersea sensing based on product line principles using the tenets of the Joint Data Labs (JDL) data fusion model. The reference architecture work was completed as a capstone report (Bones, 2018).

Specifically, the capstone report examined the concept of combining mobile and stationary underwater sensors into a coherent, distributive network. The project presented a baseline architecture for a data fusion system that facilitates the near real-time exchange of information from disparate sources. This architecture, in turn, provides a basis for further system development, and can guide future studies of relevant data/information fusion concepts and technologies for applications to anti-submarine warfare (ASW) and mine warfare. The study used the unique approach of inverse systems engineering to design an architecture based on the ASW kill chain, and the probability of success in detecting, classifying and tracking underwater objects. The resulting probability of success was then measured against the probability of success of a human ASW operator to determine the adequacy of design. ExtendSim software was used o model and simulate the architecture to validate functional capability and improved performance over the human ASW operator. The resulting architecture can facilitate the successful integration of passive acoustic sensor information with intelligence products and timely distribution of fused data across manned and unmanned platforms. The architecture also allows for future growth into active acoustic sources, environmental data sources, non-traditional ASW sources such as radar, and electronic support measures (ESM).

Keywords: *data fusion architecture, ASW, mine warfare, underwater sensors, product line*

Background
The underwater domain is one of the most challenging realms for naval operations. With the increasing sophistication of autonomous underwater vehicles (AUVs) and their improved sensor payloads combined with more traditional underwater sensor systems, there is a need to be able to integrate these various sources into a distributed network. Given the increased volume of data that will occur, there is a need for a data fusion architecture that integrates the output from various sources into coherent information. Also, given the rapid changes in data fusion technology, there is a need for a systems-engineered, product-line approach that captures the state-of-the -art and provides a framework for the integration of technology advances as they occur.

As it currently stands, the human operator solely provides the data fusion capability for the ASW environment. A console operator analyzes the output from multiple sensors, determines the relevant information, and combines that information to create a contact in the digital environment. The digital nature of the contact allows the operator to share the contact with other networked systems. The contact must be frequently updated using information from the sensors to ensure that system portrays accurate information. Since the input from the sensors must be manually integrated and the contact frequently updated, oversaturation of information to the user may occur.

This oversaturation may result in the expiration of the relevant information due to the lack of timely integration into the contact. The current system is bottlenecked by the human operator. Replacing the human operator with an autonomous system allows for increased efficiency and a resultant increase in accuracy due to a reduction in the delay associated with the implementation of sensor information. The automated system also allows for the utilization of more sensor data. Since the human operator can only look at one sensor at a time, it acts as a system in series while the autonomous system can implement information from multiple sources at once and thus acts as a system in parallel.

The capstone team utilized *The Handbook of Multisensor Data Fusion* (Liggins, 2009) as the main resource for previous work. The handbook provided an excellent primer on multi-sensor data fusion architecture. In particular, the handbook addresses the systems engineering concerns and process for developing a data fusion architecture. The text generalizes all data fusion systems and does not specify the constraints and requirements for undersea sensor fusion. Additional domain specific references relevant to the architecture development are:

1. Damianos Gavalas, Aristides Mpitziopoulos, Grammati Pantziou, Charalampos Konstantopoulos; "An Approach for Near-Optimal Distributed Data Fusion in Wireless Sensor Networks." *Wireless Networks,* July 2010, Springer Science Business Media, LLC
2. Hongmei He, Zhenhuan Zhu, and Erkki Makinen, "Task-Oriented Distributed Data Fusion in Autonomous Wireless Sensor Networks." *Soft Computing* Volume 500 August 2014, Springer Berlin Heidelberg
3. Jaime Esteban, Andrew Starr, Robert Willetts, Paul Hannah, and Peter Bryanston-Cross; "A Review of Data Fusion Models and Architectures: Towards Engineering Guidelines." The University of Manchester School of Mechanical, Aerospace and Civil Engineering, Manchester, M60 1QD, UK;
4. John Heidemann, Milicia Stojanovic, and Michelle Zorzi; "Underwater Sensor Networks: Applications, Advances, and Challenges" Philosophical Transactions of the Royal Society; http://rsta.royalsocietypublishing.org

At this time, no current capability utilizes the JDL data fusion architecture in a near real-time ASW environment. The ASW data fusion architecture builds upon the JDL model, refining the data fusion concept with the specific context of ASW data fusion utilizing current and future ASW platforms and sensors.

Findings and Conclusions

The initial research objectives focused on model development including models for information structure, evidential reasoning, and situation awareness. The model development process used the following steps:

1. Develop requisite domain requirements models based on the JDL data fusion model
2. Develop notional variability models
3. Develop a notional domain architecture
4. Develop application requirements models

The study used the novel approach of inverse systems engineering to design an architecture based on the ASW kill chain and the probability of success in detecting, classifying, and tracking underwater objects. The probability of success is then measured against the same probability of success of a human ASW operator to determine the adequacy of design.

Integration Definition for Process Modeling (IDEF0) diagrams were used to develop multi-tiered IDEF0 diagrams as the initial step of defining the functional architecture. The IDEF0 diagrams allowed the team to define the inputs, outputs, and controls for each of the ASW data fusion operational activities. The development of the IDEF0 diagrams contributed to the development of multi-tiered functional flow block diagrams (FFBD), and further refine the functional architecture by depicting the time-ordered sequence of the operational activities.

No system exists for combining mobile and stationary underwater sensors into a coherent, distributive network. Without a data fusion system, a limitation exists for strategic/theater planners and tactical operators to accurately identify undersea threats/targets, maintain maritime superiority, and efficiently allocate resources. The project results provide an ASW data fusion architecture that builds upon the JDL process model. The utilization of a top-down systems engineering process allowed for the development of an architecture that satisfies the technological gap that currently exists. The benchmark used to determine the success of the architecture is the human ASW operator/analyst, the current ASW data fusion process. Utilizing Markov analysis, the proposed ASW data fusion architecture consistently exceeds the performance standards of a human ASW operator. The results support the conclusion that the ASW data fusion architecture exceeds the performance standards of the existing human ASW operator.

A side excursion examined the architecture requirements for the data fusion data base, and the applicability of using artificial intelligence to perform fusion and target recognition.

Recommendations for Further Research

The ASW data fusion architecture is presented as a generic architecture for data fusion. There is much more research and development required to further the team's proposal towards a functional system. The following are recommendations for future research.

(1) Development of subsystems - The subsystems used to develop the ASW data fusion architecture are "black box" subsystems. Each subsystem has a function it must accomplish, but the architecture developed in this project intentionally does not specify how each function is accomplished. Future research should include an investigation to existing subsystems and commercial off-the-shelf systems capable of meeting the system requirements.

(2) Integration of future sensors - This project limits the scope of sensor inputs to passive acoustic sensors. Future research should be conducted to determine how to best integrate other sensors, such as active sensors, environmental data sensors, optical sensors, radar and other sensors that could be used to enhance ASW applications further.

(3) Integration of acoustic intelligence (ACINT) database - This project included the use of the ACINT database for contact classification but does not specify how this information is received, utilized, or integrated into the system. Future research and design to integrate this database into an ASW data fusion system is required to substantially aid in the identification of contacts based on the acoustic data received.

(4) Impact of environmental data - Environmental conditions substantially impact the performance of all acoustic sensors. This project does not consider the acoustic environment. Future research is required to assess and incorporate environmental conditions (e.g., temperature, depth, stratification of water based on temperature (layering), bottom composition, and salinity) that have an impact to acoustic sensor performance.

(5) Expansion of tracking capabilities - This project did not investigate the requirements to track a contact; rather it focused on fusing information from multiple sensors to develop a contact with the potential of being tracked and identified. Future research on the utilization of the data output from this system should include expanded options for contact tracking over a given period, with the result being weapons targetable information.

(6) Development of rules and algorithms - For the data fusion architecture to function, there must be an established set of rules to determine what constitutes a feature, cluster, and contact. Future research should focus on developing these rules for the construction of an algorithm to analyze the incoming acoustic data and aid in the automated process of identification.

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NPS-18-N142-A: Advancing Post Mission Debrief and Data Collection Using a Sociotechnical System Design Approach

Researcher(s): Dr. Karen Holness
Student Participation: Mr. Richard Bee CIV, Mr. Joshua Considine CIV, Mr. Kevin Friedemann CIV, Mr. Tyler Hallenbeck CIV, Mr. David Heinzer CIV, Mr. Charles Junghans CIV, and LCDR Daniel Moran USN

Project Summary

Using a sociotechnical system (STS) approach, this research evaluated various aspects of post mission data collection and analysis for F/18 flight training events. The project principal investigator (PI) initially conducted in-person interviews with Subject Matter Experts (SMEs) on this process. Using the interview responses, an initial STS process and variance analysis was performed, resulting in a set of system capability requirements. These requirements and an initial process model were provided to a seven-member team of Naval Postgraduate School (NPS) systems engineering distance learning students. For their capstone project, the team conducted their own stakeholder and pilot representative interviews and created additional process models and entity relationship diagrams. The capability requirements provided by the PI were included in their feasibility assessment of design alternatives they created. After ranking the design alternatives with a Pugh matrix, task completion times for the highest scoring alternatives were further evaluated using simulation software and statistical analysis, resulting in a recommended automated event detection configuration. The PI also interviewed four F/A-18 pilot instructors, and incorporated the data into updated variance, function allocation, and requirements analyses that integrated the previous results completed by the PI and the capstone team. The PI proposed a set of system performance requirements that reflected proposed training site workspaces containing recommended hardware, software, and personnel configurations. These results are expected to be revisited in the planned FY19 Naval Research Program (NRP) study to further explore the policy, environmental, and organizational impacts on the conduct of F/18 flight training events.

Keywords: naval aviation; flight training events; post mission analysis; human performance; sociotechnical systems; systems engineering

Background

The needs analysis phase of the systems engineering (SE) process typically includes some level of gap analysis. The differences between the "as-is" state of the current system, compared to a desired "to-be" state of the system forms the basis for capability requirements that drive the remaining SE phases to design, build, test, and field a new system configuration.

As defined by Taylor and Felten (1993), any organization, including service organizations, that (1) uses technology in its processes to convert inputs to outputs (e.g., has a technological subsystem); (2) uses people to coordinate process activities and to maintain the integrity of the organization itself (social subsystem); and (3) accounts for factors external to the organization and their impacts on its processes, inputs, and outputs (environmental subsystem), is in fact a sociotechnical system. The majority of systems used within the Navy, Marine Corps, and Department of Defense (DoD) that require human interaction with hardware and software to execute a mission or concept of operations (CONOPS) can be considered STSs. This includes post mission analysis systems as well. The process of conducting a post mission data collection and analysis involves human-human discussions supported by human-software interactions to retrieve and assess mission execution data.

Key elements of STS analysis methodology includes (1) an evaluation of the current hardware/software/human configurations and processes used, (2) an investigation into known process variances and current mitigations of those variances, and (3) a function allocation assessment to determine which parts of the process would be better executed by humans versus automation.

A challenge for human systems integration (HSI) is the development and implementation of measurable HSI specific performance requirements at the platform or "whole-system" level, and their addition to the system capability and SE requirements documents used to design/build/test the required system. By leveraging standard processes and guidelines for developing performance requirements, HSI and STS requirements for post mission data collection and analysis would identify the critical human-human and human-automation interactions, based on the identified key variances and the function allocation analysis. With valid supporting data on expected system performance, these requirements can be justified and translated into other programmatic metrics such as system cost and schedule via separate cost-benefit analyses.

Findings and Conclusions

This project responded to the OPNAV N9 Warfare Systems' NRP topic NPS-18-N142, titled "Advancing Post Mission Debrief and Data Collection"; it expressed an interest in investigating automation options to support these processes. The use of STS and SE methodologies provided additional perspectives on the factors that impact the ability of F/A-18 flight training event personnel to capture, analyze, store, and share performance assessment data.

To achieve the research objective and answer the research questions, the Principal Investigator for the project, also the author of this report, initially conducted in-person interviews with two flight training event SMEs. The Naval Postgraduate School Institutional Review Board (IRB) reviewed the interview protocol and determined their conduct was not human subjects' research.

Each interview lasted no more than 1.5-2 hours. Using the responses from these interviews, an initial STS process and variance analysis was performed, resulting in a set of aircrew performance measurement (APM) system capability requirements. These capability requirements reflect the fact that the current data collection and analysis process relies heavily on human observations, handwritten notes, and data manually entered onto paper scorecards and grade sheets. There is a layering of information and interpreted data that is entered on the handwritten notes, grade sheets and scorecards. During the course of the data consolidation and analysis process, this information and data is revisited multiple times, and may be edited, when new information and data is obtained from the aircrew, instructors, and other relevant personnel participating in the flight training event.

These requirements and an initial process model were provided to a seven-member team of NPS systems engineering distance learning students. For their capstone project, these students were asked to do the following: (1) perform a comprehensive literature review and trade study on post mission data collection and analysis, and available software tools to support mission debrief of flight training events, (2) create system requirements based on a set of stakeholder capability requirements to be provided no later than 31 March 2018, and (3) use model-based system engineering to identify feasible system design options with increased levels of automation that address the stakeholder capability requirements.

To complete their project, the capstone team conducted their own stakeholder and pilot representative interviews (also NPS IRB determined as not human subjects research). Using this data, they created process models and entity relationship diagrams in the CORE software. The APM capability requirements provided by the PI were included in their analysis as part of a feasibility assessment for the design alternatives they created. After ranking their design alternatives with a Pugh matrix, task completion times for each of the highest scoring alternatives were further evaluated using the CORE simulation engine. The average times from the subsequent simulation runs were analyzed using a single factor Analysis of Variance and Fisher's Least Significant Difference method. Based on these results, one design alternative was recommended. A final capstone report was created to complete their SE degree requirement.

Finally, the PI also interviewed four F/A-18 pilot instructors, and incorporated the data in an updated STS analysis that integrated the previous results completed by the PI and the capstone team. From these results, a workspace located near the airfield/hangar at a training site was proposed. This workspace would contain at least one workstation dedicated to capturing all relevant aircraft and aircrew data needed to evaluate the aircrew and flight training event performance metrics. An alternative workspace dedicated to all briefing, coordination, data exchange, and data analysis activities was also proposed. The PI created a set of system performance requirements that reflected proposed training site workspaces and their recommended hardware, software, and personnel configurations. The requirements can be used by the topic sponsor to further evaluate current technologies that are considered as candidate improvements to current training site hardware and software configurations.

Recommendations for Further Research

The analyses performed in this study are subjective and reflect the understanding of personnel outside of the flight training event process. Therefore, it is worth revisiting the variance coding and the function allocation analysis with the same and additional pilot instructors, flight training event SMEs, and F/A-18 stakeholders to better reflect their inputs into the proposed STS redesign. It is also worth updating the CORE model to reflect any changes to the proposed APM system configuration that results from these additional inputs. A follow-on study to this project was approved for FY19 funding by the NRP. The goal of the NPS-19-N119-A study is to evaluate the organizational and environmental STS interactions necessary to engineer and implement an improved STS design for F/A-18 flight training events. An in-depth evaluation of the current internal and external systems that influence the planning, resourcing, and execution of F/A-18 flight training events will be conducted, including an assessment of policy, guidance, requirements, and organizational interactions. Proposed modifications to these environmental interactions in support of the STS requirements provided in this report are the expected deliverables of this FY19 project.

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NPS-18-N167-B: Contribution of Autonomous Surface Vessels to Distributed Lethality and Supporting Communications/Data Link Requirements

Researcher(s): Mr. David Trask and Dr. Shelley Gallup
Student Participation: LT John F. Tanalega USN

Project Summary

The study built on work underway at the Naval Postgraduate School (NPS) on the Defense Advanced Research Projects Agency (DARPA) Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessel (ACTUV) program. The ACTUV, christened SEA HUNTER, is an experimental autonomous unmanned vessel undergoing test and evaluation under the direction of the Office of Naval Research (ONR) and Space and Naval Warfare Systems Command (SPAWAR) Systems Center Pacific (SSC Pacific) in San Diego. The research used data from the ACTUV Missions Workshop (Feb 2017) to develop prospective mission sets, one of which addressed the use of ACTUV as a contributing force in a Distributed Lethality (DL) scenario. The employment options were modeled in Lightweight Interstitials Toolbox for Mission Engineering Using Simulation (LITMUS), and results were modified to achieve the best possible outcome. The work, mostly conducted by LT John Tanalega, USN, revealed autonomous systems, such as ACTUV, now designated by the Navy as the Medium Displacement Unmanned Surface Vessel (MDUSV), contribute significant value to the DL mission. Additionally, the analysis revealed the tactical actions, or "behaviors", necessary for unmanned systems, such as SEA HUNTER, to seamlessly join the fleet as a fully capable resource in tactical engagements. The systems necessary to sense, detect, inform, decide and then conduct the appropriate behavior were examined by a team of students from the Systems Engineering Department who provided a comprehensive report on their findings.

Keywords: *MDUSV, ACTUV, Distributed Lethality, unmanned, autonomous, SEA HUNTER*

Background

The DARPA funded NPS to conduct research in support of the ACTUV program starting in FY16 and concluding in FY18. The ACTUV program's main objective was to prove an unmanned, autonomous vessel could safely operate in accordance with standard maritime Collision Regulations (COLREGS). A test vessel was used to prove out the sensor and software necessary to conduct operations which were later ported to the actual test vessel, christened SEA HUNTER, a 132-foot-long trimaran. The ACTUV project was transferred to ONR control in 2017. ONR continues to test the ship's compliance to COLREGS and achieved a milestone in July 2018 when the ship conducted a test mission without a human on board.

The topic sponsor, OPNAV N96 Surface Warfare Directorate, is responsible for the Navy's Future Force Structure plans and is keenly interested in understanding what it is going to take to bring MDUSVs into the fleet. The use of unmanned vessels, and more specifically, autonomous vessels is in its infancy, leaving much room for research to identify the missions and required capabilities prior to conducting a major acquisition program. There is no doubt such a program will eventually exist as many studies and force structure analysis all indicate the need to procure unmanned vessels as a compliment to the manned fleet. Driving this is the perceived value analysis indicating much lower acquisition and life cycle costs. Although this may be true, the capability to accomplish the required missions is unproven. Our research moved the ball forward by identifying the value of MDUSVs in conjunction with other Navy assets to the Distributed Lethality concept of operations. It also clearly demonstrated that it is absolutely essential that behaviors necessary to conduct this mission as well as the supporting mission equipment, sensors, and potentially weapons load must be developed.

Findings and Conclusions

The project started by defining the problem. Distributed Lethality is defined as the operational and organizational principle for achieving and sustaining sea control at will and is composed of three tenets: increase the offensive lethality of all warships, distribute offensive capability geographically, and give ships the right mix of resources to persist in a fight.

The methodology consisted of a literature search to get background information on distributed lethality, future force structure, unmanned surface vessel programs, appropriate simulations, faculty members engaged in research applicable to the project, and potential students interested in conducting thesis research in support of the project.

Based on the future fleet studies provided to N96, the research focused on two objectives: define some operational mission for a small number of USVs, and define the systems engineering necessary to implement autonomous behaviors appropriate to that mission.

The research reached out to faculty in the Operations Research (OR) and Systems Engineering (SE) Departments to address both issues. What is the operational value of an MDUSV, and what systems engineering principles and designs are required to generate operational tactics on an autonomous ship?

The first question was addressed by LT John Tanalega in his thesis, "Analyzing Unmanned Surface Tactics with the Lightweight Interstitials Toolbox for Mission Engineering Using Simulation (LITMUS)". The measure of effectiveness for the simulation was which force, Blue or Red, was first to fire (FTF) an effective salvo at the other. Without MDUSV, the Blue surface action group (SAG) was FTF only 19% of the time while adding MDUSV to the mix resulted in an increase to 56% FTF. LT Tanalega summed up his findings with the following words. In 1805, Vice Admiral Horatio Nelson famously said, "…no captain can do very wrong who places his ship alongside that of the enemy." LT Tanalega's conclusion in 2018 is, "…no captain can do very wrong who places MDUSV between his ship and the enemy."

The systems engineering team defined the relationship of ship systems to the mission and developed comprehensive descriptions of the relationships and information sharing necessary to implement autonomous behaviors that were tactically relevant to distributed lethality operations. This work is fundamental to future developmental activities.

Recommendations for Further Research

The use of unmanned autonomous surface vessels (UASVs) is a key combat enabler for the future fleet. Much as the use of unmanned aerial vehicles such as Predator and Global Hawk have changed the face of air operations, substantial numbers of UASVs will enable distributed operations at lower cost. The key is to understand the mission best suited to the vessels, and the requisite combination of autonomy and systems necessary to successfully conduct those missions. Further analysis, simulation, and study are needed to implement and define the acquisition of this capability.

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NPS-18-N169-A: An Analysis of the Ability to Defend Strategic Chokepoint with a Combined Force of Manned, Unmanned and Autonomous Subsurface, Surface and Air Assets

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Project Summary

The project evaluated methods of employment and concepts of operations for unmanned systems in the defense of chokepoints, to include feasibility and challenges of unmanned systems as primary lines of defense. This course of action is driven by the shrinking submarine force called upon to conduct other higher priority missions. The belief is that autonomous unmanned systems operating in conjunction with traditional surface and air platforms may offer alternatives for, or augmentation to, manned submarines in the defense of chokepoints.

Keywords: *defense of chokepoints; autonomous, unmanned, surface vessels*

Background

The sponsor is keenly interested in the value of adding unmanned autonomous surface vessels (UASVs) to the fleet in order to gain greater warfighting capability at lower cost. The Defense Advanced Research Projects Agency (DARPA)'s anti-submarine warfare (ASW) Continuous Trail Unmanned Vessel (ACTUV) program delivered a 132ft fully autonomous, unmanned ship capable of carrying 20 tons of sensors and/or weapons at a total first build cost of $22M. The ship is being tested under Office of Naval Research (ONR) direction by Space and Naval Warfare Systems Command (SPAWAR) Systems Center Pacific (SSC Pacific) in San Diego and has demonstrated long duration, unmanned operations in the open ocean. This is the primary data point for extrapolating a UASV fleet capable of conducting operations to monitor and hold a chokepoint. In addition, modeling indicates communications with airborne surveillance systems such as broad area maritime surveillance (BAMS) and Boeing P-8 Poseidon can significantly enhance lethality should the chokepoint be challenged by sea or undersea forces.

Findings and Conclusions

A number of previous studies were instrumental to this project. LCDR Kevin Solem's thesis, reported teaming the Boeing P-8 Poseidon with ACTUV in a tactical ASW scenario increased the probability of kill and decreased the time to kill. This effort was used as the basis for a capstone report from the Systems Engineering (SE) 320 class which defined the functional and physical architecture for a theater anti-submarine warfare (TASW) mission package deployed on a Medium Displacement Unmanned Surface Vessel (MDUSV). Together, the two study efforts define the value of the UASV as well as the functional and physical systems architecture necessary to the TASW mission.

The SE320 capstone provided a comprehensive analysis of the TASW mission requirements for holding a chokepoint. The team defined the mission or problem and conducted an operational analysis to determine what the system will do and why. This was followed by a functional architecture which defined capabilities needed to meet each operational requirement. They then created a physical architecture to define the generic systems and interfaces necessary to enable the architecture requirements. The final step was to assess the architecture to validate performance and shortfalls.

The findings were significant. The sonar capabilities were determined insufficient to the TASW mission due to size and weight constraints of the MDUSV. Although algorithm development is progressing, they do not provide automated classification of submarines without human in-the-loop interaction. Autonomous coordinated search and track algorithm developments are underway but far from operational.

Recommendations for Further Research

The recommended actions for further research follow directly from the findings of the SE320 report.

- Develop an acoustic performance model to determine minimum sonar array characteristics necessary for TASW mission package passive detection and tracking of a submarine in a variety of sonar environments.
- Perform a feasibility analysis of sonar system integration with the MDUSV to include the combination of a towed sonar system and a Sonobuoy Launcher System.
- Expand analysis of autonomous search and track tactics to maximize search, localization, and tracking performance in a variety of acoustic environments based on projected sonar performance. This includes algorithms for autonomous coordination of search and track patterns to include dynamic shifts for planned interruptions, such as interrogation of a POSSUB, or unplanned interruptions, such as secondary contact avoidance or sensor failure of one unit in a group.
- Create algorithms to support autonomous development of collaborative area of uncertainty (AOU) using multiple expansion rates as identified in the function Localize Contact (FN.1.2.3) in Section IV.C.2.b of this report.
- Create machine learning algorithms to support autonomous classification of sonar contacts, integrated with surface search sensors such as radar detection of surface contacts, as identified in Section III.A.4.b of this report.
- Perform a feasibility analysis of data fusion using Link 16 or Link 22 J-series messages to pass TASW mission data to enable collaborative TASW.

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NPS-18-N174-A: Quantifying the Military Value of an LHA Expanded Adaptive Force Package: AMERICA Class Surface Action Group (SAG)

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Project Summary

Using a series of campaign analyses, wargaming, systems analysis studies, and systems engineering, this research analyzes the offensive effectiveness of an adaptive force package (AFP) composed of an AMERICA class amphibious assault ship (LHA) equipped with the Lightning II Joint Strike

Fighter STOVL Variant aircraft (F-35B), unmanned air and surface platforms, and various numbers of Guided Missile Destroyers (DDGs) and littoral combat ships (LCSs). Offensive anti-surface warfare (ASUW) is the focused mission area, however, increased vulnerability to the LHA is also explored. Emerging themes and findings include the following. Augmented by the Marine Corps Air-Ground Task Force (MAGTF) Unmanned Aerial Systems (UAS) Expeditionary Experimental tiltrotor system (MUX), the LHA Air Combat Element (ACE) adds significant intelligence, surveillance, and reconnaissance (ISR) and communications relay capability to a traditional surface action group. The air combat element (ACE)'s F-35B can add a robust anti-ship cruise missile (ASCM) and ISR capabilities to a traditional surface action group. To best be configured for a sea control mission including air defense, the ACE on the LHA will need to be augmented with additional F-35Bs at a significant cost to rotary-wing/tiltrotor assault-support lift.

Keywords: *naval tactics, naval operations, naval concept development, LHA, sea control, campaign analysis, wargaming*

Background

Increasingly, the U.S. Navy must concern itself with sea control operations inside contested environments, particularly as potential adversaries are developing new capabilities with sufficient capacity to challenge U.S. maritime operations. New concepts like Distributed Maritime Operations and Multi-Domain Operations are being explored while alternative force structures and tactics are evaluated to better employ the fleet in challenging environments. One proposal is to leverage capabilities existing in AMERICA (LHA6) and an air wing that includes the F35B aircraft to create an expanded adaptive force package (EAFP). The EAFP is composed of a traditional surface action group, AMERICA equipped with F35Bs, and unmanned systems to enhance their offensive power. This research effort explored the advantages of an EAFP in a contested environment and quantified the value of the LHA to host elevated ISR, comms, and weapon platforms for the traditional surface action group.

Findings and Conclusions

This analytical effort was conducted in a series of campaign analyses, a wargame, a systems analysis study, and a system engineering study (still in progress as a thesis). These activities occurred as capstone classroom projects, as graduation capstone projects, and theses research. It involved students from both the Navy and Marine Corps with game players from all services. Products from each of these efforts were provided directly to the sponsor, but are summarized here.

A common future wartime scenario was used across the research efforts involving a 2032 conflict in the South China Sea where the adversary occupies the Indonesian island of Natuna Besar. Allied expeditionary forces are tasked with obtaining sea access to and seizing the island. A ZUMWALT Surface Action Group and an AMERICA EAFP are tasked with advanced force operations and face robust adversary surface combatants, shore-based anti-ship cruise missiles, and J-20 aircraft stationed on Natuna Besar. The tactical situation, force locations, and system capabilities were derived from unclassified sources.

The first analytical effort was conducted as part of the NPS Joint Campaign Analysis class by three Marine officers and one Army officer. This team found that the LHA-6 aviation component provides more lethal, responsive, and survivable strike reconnaissance capabilities than the next generation unmanned aerial vehicles organic to the surface action group (SAG). This observation is critical since they show that failing to locate an entire enemy force--inclusive of distributed and auxiliary units--results in a high risk of counter-fire and potential defeat. However, the normally assigned six F-35Bs are shown to be insufficient to defeat fifteen shore-based J-20s and be available for follow-on expeditionary operations. Additional F-35s from expeditionary basing and/or additional amphibious ships and/or a carrier air wing are desired to fulfill the advanced force air defense requirements.

Lessons from the campaign analysis effort were adopted into a follow-on wargame design, development and execution effort. Wargaming students, including some who worked the previous quarter's campaign analyses, worked with NSWCDD programmers in coordination with another research program to build a computer-aided wargame using the same scenario. Players were recruited from NPS officer-students across campus. From this game several observations were noted on the tactical employment of the SAG and EAFP. The first was that both Blue and Red used manned tactical aircraft as their first choice of ISR, while the remaining forces were held in the most restrictive electronic emission control. ZUMWALT was employed further forward the threat axis than any other Blue platform to leverage her capabilities and act as a command platform, while the LHA remained within flight range of the island objective but as far away as possible to minimize risk. The tactical situation and need for information caused players to modify their emission control status, but only for brief periods of time. Unmanned surface vessels were used primarily as active decoys off-axis from the EAPF and SAG in an attempt to seduce Red to electronically expose their location.

From these lessons a group of three Masters of Systems Analysis students conducted their capstone project using the campaign analysis and wargaming results to further assess what the current Marine Expeditionary Unit (MEU) ACE composition can provide in sea control capabilities. Additionally, they sought to determine the best possible sea control ACE composition using current or near-future manned and unmanned aviation platforms aboard AMERICA. Using mission analyses in ISR, communication relay, ASUW, and air defense, the team found a current MAW configuration marginally improved the current ISR and ASUW capabilities of the traditional SAG, with only minimal contribution in C3 and air defense. However, with the addition of seven Marine Air-Ground Task Force (MAGTF) Unmanned Aerial System (UAS), Expeditionary (MUX) an LHA and sea control configured ACE can significantly enhance both ISR and C3 capabilities of the traditional SAG. To considerably improve the air defense capability, additional F-35Bs are required which severely affect the expeditionary lift capacity of the ACE.

The final effort in this series of research initiatives uses systems engineering with functional architecting to identify metrics for lethality effectiveness and blue vulnerability. This work is followed by combat modeling to assess these metrics. This research is in progress by LT Gregory DeJute, USN. It will be finalized and forwarded to sponsors in December 2018. Initial results indicate evidence that if the F-35B is equipped to employ the Navy's Integrated Fire Control-Counter Air (NIFC-CA) and guide the surface launched SM-6, there is both an increased lethality and decreased vulnerability for the EAFP when compared to the traditional SAG. However, this comes with up to a 20% risk of experiencing combat damage to the LHA.

Several global observations may be made from this series of work. Most of the derived quantitative evidence confirms well established ASUW tactical principles – being able to target and launch an effective missile strike before an adversary is paramount to mission success. Increased capability and capacity in ISR and targeting--either with long range and long loiter-time unmanned systems or manned aircraft--will enhance offensive capability, as long as weapon ranges are sufficient to capitalize on the targeting improvements. That is why the MUX is the Marine Corps' largest contributor to ASUW mission area. Therefore, an argument may be made that any long range airborne ISR platform dedicated to the SAG will provide improvement without placing the LHA at risk. The addition of F35B capability to the traditional SAG does provide increase air defense capabilities and some increased ISR capability—constrained by the F35B's range. However, this comes at placing the LHA in a higher air and surface threat environment. To provide significant air defense capability in the tactical scenario studied, up to twenty F35Bs will need to be embarked (or based nearby) in order to ensure sufficient numbers remained for follow-on expeditionary requirements. These additional F-35Bs will have either a major impact on assault support lift availability—given the LHA can host the additional aircraft-- or some portion of strike and/or assault must be based ashore or on another sea-based platform. This lends evidence that expeditionary basing, a dedicated light aircraft carrier without an amphibious mission, and/or the risk to a traditional CVN/carrier air wing (CVW) should be explored when facing a robust air threat environment.

Recommendations for Further Research

Each effort described above identified areas for further research, however, the final three concepts listed in the findings should be further refined for concept development in highly contested environments: expeditionary basing, a dedicated light aircraft carrier (CVL), and operating a large nuclear aircraft carrier (CVN) within an archipelago.

NPS-18-N219-A: Future Fleet Wargames - Post Wargame Experimentation and Analysis

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Project Summary

This project's goal was to establish an ability for the Navy's N9 Warfare Systems Directorate to develop insights regarding the impact of planned and scheduled future naval capabilities on the operational success of U.S. naval forces. To accomplish this goal, research efforts combined systems engineering, operations research, and modeling and simulation to develop an Integration and Operations Support System (IOSS) that provides an experimentation environment to assist in forming a solid cost position for technological and doctrinal change, while identifying trade space for balancing budgetary and security issues. The IOSS is an innovative use of scenario methodologies, computer simulation, and experimentation to shape a strategic analysis framework for mission engineering, based on a scenario from an actual computer aided exercise, Cobra Gold 2018 (CG18). The Joint Theater Level Simulation (JTLS) drives the operational vignettes for the training audience in this multinational exercise. Our approach was to automate the CG18 exercise, thereby creating a repeatable experimentation environment in which a knowledgeable team could form credible, analytically derived insights about the potential impacts of introducing new systems. We generalized this approach and provided a proof-of-concept demonstration by using IOSS to investigate the effects of introducing future unmanned aerial and underwater systems into an operational context.

Keywords: *capabilities, scenarios, methodologies, experimentation, Joint Theater Level Simulation, JTLS*

Background

The United States and its allies will continue to face an evolving set of challenges in a multipolar, dynamic, and complex strategic and operational environment. As a preeminent instrument of force projection, the U.S. Navy is critical to achieving the nation's strategic goals within this exigent global environment. The agility and ability of the U.S. military to engage in potential multiple, simultaneous actions is stretched to such a degree that resource limitations threaten to erode the flexibility that U.S. forces may require to effectively respond. The United States National Defense Authorization Act for Fiscal Year 2017 (United States House of Representatives 2016), recognized that emphasis on systems engineering and coordination of major interfaces among the military departments is necessary to leverage current and future capabilities towards mission success, a concept labeled "mission integration management". Within the Department of the Navy staff, the N9 Warfare Systems Directorate seeks innovative methods to analyze the composition of the future fleet based on new capability insertions that can ensure mission success, while satisfying budget concerns.

The overarching research question that N9 wishes to address is, "What set of new capabilities will most increase the future fleet's operational effectiveness?" Underlying this primary issue are more defined questions that shape the approach that the NPS team applied:

- What new capabilities have the greatest effect on success for a given mission set?
- What combination of new capabilities and legacy systems have the greatest probability of success in a given operational environment?
- What combination of new and legacy systems provides the most robustness for a range of operational missions?
- What are the relative costs of achieving degrees of success in a given operational environment?

Findings and Conclusions

This research's overall approach to addressing N9's questions was to extend the concept of mission engineering (ME) to include continuous analysis (mission engineering and analysis, or MEA), and to develop and demonstrate an analytic support tool for MEA. Gold (2017) defines mission engineering (ME) as the "deliberate planning, analyzing, organizing, and integrating of current and emerging operational and system capabilities to achieve desired warfighting mission effects." From an engineering perspective, the system of interest (SoI) is the "mission," where different weapon systems are just one category of components (Wasson 2016). The system lifecycle is the period from which the conflict situation first emerges to when the mission is accomplished. There are three major processes in the ME lifecycle: system acquisition, system integration into a system of systems (SoS) architecture, and actual operations that execute the mission plan. Hernandez, Karimova, and Nelson (2017) refined the initial definition of ME by including mission and support plans as part of the SoI, and highlighted continuous analysis to inform transitions between ME processes. The result is MEA. MEA emphasizes on how systems engineering (SE) and systems analysis (SA) techniques reinforce the primary processes employed during mission planning and execution (Hernandez et al. 2017).

A methodology that transforms a human-in-the-loop (HITL) computer assisted exercise (CAE) into a replicable computer aided wargame (CAW) is the basis for the MEA analytic support tool called the Integration and Operations Support System, or IOSS. The IOSS provides a simulation environment that supports the analysis of future capabilities. The IOSS is a fundamental, but critical step in building analytic support tools for MEA. An actual CAE (Cobra Gold 2018 or CG18) is the basis of the working scenario for the IOSS. CG18 was a multinational exercise consisting of live and virtual military units from Indonesia, Japan, Malaysia, Singapore, South Korea, Thailand, and the United States. Interagency and non-governmental agencies also played major roles in the operational scenario. Virtual operations within the CAE occurred in a fictional landmass called Pacifica. A multinational force used combined air, land, and sea power to meet its mission and perform a number of key tasks. These tasks included achieving air superiority, peace enforcement, maritime interdiction, counter piracy, and humanitarian assistance.

To elicit response from the training audience in CG18, the exercise sponsor employed the Joint Theater Level Simulation (JTLS), which has supported unified commands in training exercises for over 35 years. The most current version of the simulation is JTLS – Global Operations (JTLS – GO), an interactive, internet-enabled application. For our purposes, we refer to JTLS – GO simply as JTLS. Originally designed as a tool for development and analysis of joint, combined, and coalition operations, it models multi-sided operations with logistics, special operations forces, and intelligence support. Today, combatant commands use JTLS primarily as a theater-independent training support model.

The CG18 scenario had the necessary elements for an analyst to investigate the performance of current, new, or envisioned systems. From this scenario, specific vignettes make it possible to stress a system and visualize its relationship within a network of systems and physical surroundings. The exercise scenario was rich with conflict situations and numerous vignettes to examine different topics and systems. In model-based SE and modeling and simulation-based SE, the operational environment is fused into a scenario (Clymer 2009; Gianni et al. 2015). An accepted system model enters the simulated scenario so that stakeholders can gain shared insights about it. Data collection to support evaluation of system performance and conceptualization of system employment are two major reasons for using models and computer simulations (Clymer 2009). The project team's overall intent was to automate the CAE and to create a structure for scientific experiments on the model of a new system.

Data collection occurred in Thailand in February 2018 during the execution of CG18. Automating the activities in a scenario required reconstruction of the storyline in which certain conditions preceded decisions and actions. Therefore, the data collection effort focused on the data elements that are necessary for creating a scenario (Perla and Curry 2011). Data collection recorded end-to-end discussions and the ensuing JTLS orders that culminated into activities and outcomes. The data collection team stationed members in response cells where JTLS players communicated with the training audience and technicians to translate the training audience's operational vision into JTLS orders. Because the team's focus was on naval activities, data collectors were located in the Marine Corps cell and in the Navy cell. Data collectors also had access to the technical control cell and to the enemy cell.

Constructing the IOSS was a major effort. Taking the human out of the loop from an executed HITL game is a tremendous undertaking. The effort required automating the game mechanics and the human player. Automating the human player presented the greatest challenge. To create an automated player (AP), the team decomposed the problem into manageable parts. First, scoping the timeline to 24 hours made the number of automated decisions and activities manageable. Leveraging the JTLS internal automation further reduced complications with some tasks. The team was able to streamline mapping decisions to the desired operations, and associated JTLS orders by focusing on specific multinational force components. Subject matter experts compared the automated decisions and outcomes with the actual exercise to test the veracity of the AP's choices. While the AP in the proof-of-concept demonstration was relatively unsophisticated, future development could increase the AP's ability to handle more complicated automated decisions.

Analysts modified the JTLS's unit and system prototypes to model unmanned aerial system (UAS) and unmanned underwater vehicle (UUV) attributes that aligned with future capabilities in which the naval enterprise plans to invest. Unified commands, as well as the international JTLS users, have already accepted the JTLS unit and system templates. Analysts would manipulate the prototypes to reflect the behavior of the unmanned system. For instance, analysts could change the attributes of a small submarine to operate as a UUV with equal or enhanced speed. However, the UUV's defensive capability may be less than a manned submarine. In the case of the UAS, an ability to swarm and create an ad hoc radar system is a possibility. Two U.S. Navy students from the systems engineering curriculum presented results from UAS and UUV modeling in the IOSS in their theses published in December 2018 (Langreck 2018, Wong 2018).

The IOSS is a toolset that can provide analytically derived evidence to inform decisions. It complements existing tools that afford other perspectives while emphasizing different aspects of the new system(s) and accompanying environments. As Gibson et al. (2007) explain, system analysis is an iterative process for gaining an understanding of relevant characteristics of the SoI.

Sequential analysis can involve different research techniques at each step. We have adopted computer-based models in the IOSS. This approach can include models that can differ in fidelity, dimensionality, or operational scale. The N9 can determine the resolution and domain that they require.

The utility of the IOSS resides in the analytic rigor that it facilitates. The statistical methods that IOSS can support are a direct result from generating data samples with sufficient pedigree to withstand close examination. As such, data farming through computer experimentation is critical to the IOSS. The ability to replicate different instantiations of a scenario and initiate different random number seeds are equally important. Experimentation is a significant value added to MEA with little to no additional investment. Libraries of experimental designs are available for employment in the game setup.

Recommendations for Further Research

While the model-based systems engineering (MSBSE) approach would normally develop a scenario in which to insert the system model, this project had a readymade environment in CG18. Analysts can study different operations and vignettes for proposed UAS or UUV capabilities in the JTLS CG18 scenario. Future development of the AP could increase its sophistication and ability to handle decisions that are more complex. Once an acceptable system model is developed, the analyst can build the activities using the JTLS rules and the decision matrices for specific response cells. These studies provide an understanding of interrelationships among different variables in the scenario, which are nearly impossible to examine exhaustively due to the exponential growth in the number of interactions as the number of variables increases. Analysts can methodically study a comprehensive picture of the system for significant variables as well as important interactions (Koehler and Owen 1996).

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NPS-18-N239-A: Applying (MBSE) to Examine the Operational Effects of SH-60/MH-60 Helicopter with Enhanced Weapon Systems in a Near Peer Surface Warfare (SUW) Mission

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Project Summary
The United States Navy (USN) employs distributed maritime operations (DMO) by increasing the offensive capabilities of its surface fleet, known as adaptive force packages (AFP). One component of DMO, rotary wing aircraft supporting anti-surface warfare (ASuW), lacks a long-range weapon capability. The purpose of this project was to determine the benefit to DMO of providing the MH-60S fleet with a long-range standoff weapon capability, determine the feasibility of integrating a long-range missile (LRM) onto the MH-60S, and determine the capabilities required of that weapon system by answering the following main two project questions: How can the United States Navy use the MH-60S in greater capacity in DMO for ASuW missions, and what is the current trade space of long-range ASuW weapons that can be added to the MH-60S to affect the DMO environment? A discrete event model was created to simulate ASuW scenarios within DMO and to evaluate the effects to the established measures of effectiveness and performance. Analysis shows that the addition of LRMs provides an increased capability and reduces the overall percentage of threats to the AFP. An analysis of alternatives revealed only three available LRMs are feasible for the USN's consideration.

Keywords: *MH-60 helicopter, Naval Strike Missile, distributed maritime operations*

Background
The purpose of this project is to determine the benefit to distributed maritime operations by providing the Multi-Mission Helicopter (MH-60S) fleet with a long-range standoff weapon capability. The USN employs DMO by increasing the offensive capabilities of its surface fleet, to include cruisers, destroyers, littoral combat ships, amphibious ships, and logistics ships, and "employing them in dispersed offensive formations" (Fanta, Gumataotao, and Rowden 2015, under "Control 'Can No Longer Be Assumed'") known as adaptive force packages. This project focuses on anti-surface warfare, specifically the insertion of long-range ASuW weaponry into the arsenal of rotary-wing aircraft currently stationed aboard many ships already deployed and operating in AFPs. The goal of this new capability is to further the tenets of DMO by projecting another offensive, long-range ASuW capacity as a complement to carrier strike group/amphibious readiness group aircraft-based ASuW systems. Currently, the MH-60S supports ASuW missions but does not have long-range, beyond-line-of-sight weapon capabilities.

Mission success is defined as the ability of the MH-60S, equipped with a long-range missile, to destroy enemy targets while remaining outside the weapons engagement zone of the enemy. To evaluate the effectiveness of adding the LRM-equipped MH-60S to the AFP, we developed a discrete event simulation model. The model simulates an ASuW scenario with the MH-60S equipped with an LRM but does not simulate any particular AFP configuration. Note that the MH-60S modeled in the scenario is not restricted to use of the LRM and may also be equipped with a combination of rockets and Hellfire missiles (the specific configurations of each MH-60S were varied within the simulation model). The simulation begins after the MH-60S aircraft have launched from the AFP ships. The model assumes that the AFP will contain additional MH-60S aircraft that can be leveraged for the long-range capability, so variances in ship types within the AFP will not vary the results or analysis. For enemy threats, the Fast Attack Craft (FAC) was modeled after the Iranian Navy's Thondar class missile boat. The Fast Inshore Attack Craft (FIAC) threat was modeled after the Islamic Revolutionary Guard Corps Navy's Bladerunner 51.

Findings and Conclusions

Using a design of experiments analysis, the statistically significant simulation input factors were determined and refined. The baseline simulation was the ASuW scenario of the MH-60S with a loadout of only HELLFIRE missiles and 2.75" short-range rockets. We compared these results to simulation results of the MH-60S equipped with varying numbers of LRMs.

The lethality of the MH-60S equipped with the LRM is measured by three measures of effectiveness (MOEs): the reduction of threats that remain after the simulation, the reduction in the number of missiles fired upon the AFP, and the increase in enemy threats destroyed. These MOEs quantitatively address how overall mission success is affected by the missile's physical and performance characteristics. The MOEs are decomposed further into measures of performance (MOPs) that help to quantitatively evaluate the impacts to overall mission success.

Analysis of simulation output data showed only three significant input factors: number of FACs, number of total LRMs in the AFP, and number of FIACs. With this knowledge, additional analysis focused on significant output responses from the model: threats to the AFP, C-802 engagements, FACs destroyed, and FIACs destroyed. The response analysis indicates that the use of an MH-60S equipped with LRMs in support of an ASuW mission provides an increased capability within DMO and reduces the overall percentage of threats to the AFP. The analysis also shows that 100% of FIAC threats are destroyed in all scenarios, including the baseline; therefore, all LRMs should be reserved for FAC threats only. The increase in effectiveness of adding LRMs is relatively consistent from zero to four LRMs; however, the impact to effectiveness of bringing the total number of LRMs up to six is only beneficial when significant quantities of FAC threats are presented. If the enemy deploys five or fewer FACs, a total of four LRMs is sufficient for the AFP to defend itself. However, if the enemy deploys more than five FACs against the AFP, then a total of six LRMs is required for the AFP to best defend itself. Additionally, the analysis showed that the LRM's capability parameters, maximum range, minimum range, velocity, and probability of hitting an enemy ship, are not significant in this model, so an analysis of alternatives (AoA) of available LRMs was conducted. The AoA revealed only three feasible solutions for the USN's consideration: the Norwegian Naval Strike Missile, Turkish SOM-A, and the Israeli Delilah HL.

Recommendations for Further Research

While this data shows that the addition of the MH-60S with LRM increases the effectiveness of the AFP, further research is recommended to quantify the impact of the assumptions that were made as part of this project. Specifically, the impact of supporting systems and infrastructure is not fully understood. The simulation assumes that systems, such as data link (i.e., Link-16 or TCDL) and intelligence, surveillance and reconnaissance platforms are functioning and available at all times. Further analysis is needed to understand the impact cost of integrating and supporting an MH-60S fleet with LRMs. The further research suggested in this report will enable the USN to make more informed decisions on the development of an MH-60S fleet equipped with LRMs.

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NPS-18-N016-A: Modifying the Agent Based OSM Framework to Support Wargaming for Surface Tactics Development

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Student Participation: MAJ John King USA, CDR Daniel Cain USN, MAJ Karey Speten USAR, Capt Rachel Cline USMC, and Capt Alex Ryan USMC

Project Summary
This research advanced modification of the Navy owned agent- based model Lightweight Interstitials Toolkit for Mission Engineering Using Simulation (LITMUS) for use in a man-in-the-loop wargaming and tactical training. It is a joint effort between Naval Surface Warfare Center Dahlgren (NSWCDD) and the Naval Postgraduate School (NPS). The purpose is to develop a computer aid to assist in concept development and tactical training. After additional LITMUS program design and development was completed by NSWCDD and NPS' SEED Center, a proof of concept wargame was designed, developed, and executed using NPS Operations Research students to explore the new LITMUS gaming capabilities. Participant's observations and specific program feedback were delivered back to the LITMUS programmers.

Keywords: *wargaming, computer wargaming, naval tactics, naval concept development, agent-based modeling*

Background
Orchestrated Simulation through Modeling (OSM) is an agent-based modeling framework developed by NSWCDD. For the past two years the NPS Operations Research Simulation Experiments and Efficient Design (SEED) Center has been working cooperatively with NSWCDD modelers to create tactical scenarios inside OSM to address concept and tactical development such as anti-ship missile and unmanned combat aerial vehicle (UCAV) defense, counter-maritime Special Operations Forces (SOF) operations, and distributed lethality. OSM is the implementation core of LITMUS, which is used both in the NPS/NSWCDD efforts described above, but also to support fleet exercises. To date, these efforts have used closed form simulation. This research extends the NPS/NSWCDD cooperation to co-develop a version of LITMUS that will allow real time data input and human decisions for surface tactical wargaming and training.

Findings and Conclusions
This analytical effort's object is to create a technical demonstrator version of LITMUS that allows man-in-the-loop decisions, displays select information to players based on wargaming design and white cell input, and provides real-time adjudication.

This initiative enabled NPS gaming and programming expertise to be applied to a larger NSWCDD effort in developing a computer simulation for naval wargaming applications. The initial steps of the research developed a concept for a LITMUS version that supports a surface tactical wargaming capability with NSWCDD. Detailed tactical engagements and decisions within those engagements were designed and developed. Select engagements (surface to surface warfare) were developed to allow for man-in-the-loop decisions and beta tested with NPS faculty and students. The LITMUS programming team developed and demonstrated an initial capability for a three-station computer aided wargaming module which allowed for Red, Blue, and White gaming stations. These stations allowed players to observe "one sided" or "two sided" information upon which to base tactical decisions. Once tested and modified, the updated select engagements were demonstrated to evaluate the need for further revision. The NPS SEED Center acquired computer laptop stations and closed communication systems to support a portable environment for the LITMUS game program and player stations.

Finally, an NPS wargame was developed to test those select engagements and to provide assessment on LITMUS' ability to support tactical wargaming and education. The game was designed, developed, and executed by Operations Research students with technical assistance from the LITMUS Wargaming design team. Players were recruited from across the NPS campus. The LITMUS program, computer stations, and communication system were successfully used to execute the game. A detailed report from the game design team on LITMUS ability to support the exploration and training of surface warfare concepts was drafted and delivered to the sponsor, NPS SEED Center, and NSWCDD LITMUS designers. This included detailed programming enhancement recommendations.
The result was the successful design, development, and demonstration of a LITMUS man-in-the-loop wargame capability. NSWCDD LITMUS developers have a detailed list of recommended modifications and a new analytical tool to offer the surface navy. NPS has an updated LITMUS gaming version for use in future research in surface tactics and concept development.

Recommendations for Further Research
Further research in this area is deferred to NSWCDD program developers.

NPS-18-N105-A: Expeditionary Mine Countermeasures (ExMCM) C4I requirements

Researcher(s): Mr. Arijit Das, Dr. Sean Kragelund, and Dr. Thomas Otani
Student Participation: Mr. Jim Zhou CIV

Project Summary
The mine warfare community makes use of laptops for their various tasks. Since maintaining a large set of laptops can be burdensome, the Naval Postgraduate School (NPS) team looked at ways to alleviate this situation. The findings suggest that the laptops are needed for various functions, but in the mine detection phase the sonar files have to be distributed (due to the large volume of data) among several laptops for human analysis, thus increasing the laptop footprint. The NPS team has looked at first organizing the sonar files so they will be searchable in an easy to use manner, and also use server clusters to divide and conquer for faster processing.

Keywords: *ExMCM, C5I, UUV*

Background.
The laptop footprint problem was first suggested by the faculty at the NPS mine warfare program. The NPS team consisted of a computer scientist who was looking at the problem as a software/hardware virtualization challenge.

The topic sponsor sent reading material via email, and introduced the NPS team to mine warfare students. This helped in building some background knowledge before the visit to the Navy base in San Diego. The first stop was the mine warfare school where the staff went over all the steps involved in a mission. A mission involves planning out where the unmanned underwater vehicle (UUV) will run its scan of the depth bottom. The UUV vendor is international and is fitted with other vendor products all in one package, and the focus of this work is the sonar radar.

All work starts in the classified domain using gathered intelligence, which is then used by Mine Warfare Environmental Decision Aid Library (MEDAL) software to calculate the location and spacing of the mission. The MEDAL generated information then moves to the unclassified domain, and is used by Common Operator Interface for NSCT1 (COIN) software in planning the details of programming the UUV. COIN generated mission details are downloaded on to the UUV using Vehicle Interface Program (VIP) software. At this point the UUV is ready for data collection, and the team will then deploy and run the mission at the specified location.

On completion of the mission a few gigabytes worth of sonar files are generated in several folders. VIP is again used to offload the sonar files on to laptops. COIN is used to do post-mission analysis (PMA), which takes hours (depending on the duration of the mission). This is a human centric process, following which actual divers have to be instructed as to where to defuse the mines.
The NPS team member next met with the Shore and Expeditionary Integration Program Office (PMW-790) (SPAWAR) who programs the laptops. They decide what laptop hardware and software a mine warfare team needs from start to finish. The team takes feedback from the community to fine tune the laptops as needed. Other meetings were with Command, Control, Communications, Computers, Collaboration, and Intelligence (C5I) planners and Expeditionary Mine Countermeasures (ExMCM) company.
On return to NPS the team then organized the information in the campus knowledge portal (SAKAI). A few staff/students were asked to look at different aspects of this challenge. Most of the graduated student effort was to study the processing of data on a Hadoop Distributed File System (HDFS) platform. The other student is starting to look at file metadata. A third student has started to explore a database schema design.

Findings and Conclusions.
All laptops in use had a specific purpose to the mission, and each UUV uses a similar set of laptops. The number of laptops increased when processing of sonar files was involved. This is a manual process, and the files are divided between separate laptops. PMA does not leverage any automation software. This is a cause of major delay to the mine warfighter.

Missions are run on a regular basis, and the files are not organized in easily searchable manner. This makes it difficult to analyze historical data.

The sonar vendor provides the file format as an open source document, and it can be used to analyze the contents using a programming language like Java. A database can be used to organize the files. Sonar files can be analyzed on server cluster architecture like HDFS. This divide and conquer computing paradigm can significantly speed up the PMA.

Recommendations for Further Research.
As a first step the file metadata can be read and analyzed using a Java program, and used to create an organized store. This store could be a database to start with. A graphical user interface (GUI) can be explored to allow the community to search the files conveniently.
Next image data algorithms can be used to process the image part of the file. This will involve HDFS architecture.

NPS-18-N108-A: Surface Force Response Plan Tool

Researcher(s): Dr. Robert Dell
Student Participation: LT Eric Fields USN

Project Summary

Commander Naval Surface Forces (COMNAVSURFOR) provides appropriately manned, trained, and equipped surface forces to operational commanders to meet presence and operational requirements in accordance with various plans and directives. This research developed a management tool to assimilate all readiness metrics (manning levels, maintenance requirements, training, and ordnance loadouts) to help COMNAVSURFOR staff to understand if future requirements can be met and/or what resource gaps and shortfalls must be addressed. Optimization (integer linear programming) was used to identify the most efficient coverage of presence and operational requirements given resource constraints and to aid in gap identification. Detailed classified results are reported in the Operations Research thesis completed by LT Fields in September 2018. A demonstration to COMNAVSURFOR (VADM Brown) occurred in October 2018.

Keywords: *optimization, integer programming, integer linear programming, navy operational planner, maritime operational planning tool, decision aid, navy mission planner*

Background

Operations Research Department faculty and students at the Naval Postgraduate School have developed an impressive list of optimization models to aid with joint maritime operational planning. This planning requires the assignment of platforms over various time horizons to accomplish missions subject to a multitude of limited resources. For example, the 2016 thesis by LT Molina "Navy operational planner – undersea warfare module" provides an optimization model that plans the best assignment of surface, sub-surface, and air assets to meet undersea warfare requirements. In a related example, the 2017 thesis by LT Newman "An efficient missile loadout planning tool for operational planners" heuristically plans the assignment of missiles on ships in response to anticipated future threats. While similar, neither of these theses (or prior efforts) directly addresses the requirements of COMNAVSURFOR to provide a plan for the best use of available assets with current readiness metrics to respond to a known contingency within a given timeframe. This completed research provides this needed decision support.

Findings and Conclusions

Dr. Robert Dell and LT Eric Fields met with the sponsor at the start of the research effort to understand the maintenance, training, and deployment scheduling cycle as well as the resources and constraints in preparing ships to meet operational requirements. Readiness metrics were reviewed and sources of data identified. Discussions also provided a detailed listing of the sponsor's desire for model prescriptions to aid in scheduling and resource assignments.

Following problem identification, a mathematical formulation (an integer linear program) of objectives, variables, and constraints was written, reviewed, and refined. It was implemented in commercially available software to test its functionality and results. Real-world data was taken from sources identified by COMNAVSURFOR as input for the integer linear program. The sponsor was briefed on the initial results and invited to critique and make suggestions for improvement. A final model was completed and documented in the classified Operations Research thesis completed by LT Fields in September 2018. A demonstration to COMNAVSURFOR (VADM Brown) occurred in October 2018. LT Fields' thesis provides detailed classified findings.

Recommendations for Further Research

Future works includes programming a heuristic solver in Visual Basic for use in an EXCEL spreadsheet. This would provide COMNAVSURFOR staff access to the benefit of the optimization-based management tool on Navy/Marine Corps Intranet (NMCI) computers.

References

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NPS-18-N116-A: Expeditionary Logistics: A low-cost, Large-scale, Unmanned, Deployable Sensor Network to Support Airfield/Pier Area Damage Assessment

Researcher(s): Dr. Gurminder Singh, Mr. John Gibson, Mr. Charles Prince, and Mr. Michael McCarrin
Student Participation: LT Nicholas Davis USN

Project Summary
Airfield Damage Repair (ADR) is among the most important expeditionary activities for our military. The goal of ADR is to restore a damaged airfield to operational status as quickly as possible. Before the process of ADR can begin, however, the damage to the airfield needs to be assessed. As a result, Airfield Damage Assessment (ADA) has received considerable attention. Often in a damaged airfield, there is an expectation of unexploded ordinances, which makes ADA a slow, difficult, and dangerous process. For this reason, it is best to make ADA completely unmanned and automated. Additionally, ADA needs to be executed as quickly as possible so that ADR can begin and the airfield restored to a usable condition. Among other modalities, tower-based monitoring and remote sensor systems are often used for ADA. There is now an opportunity to investigate the use of commercial-off-the-shelf, low-cost, automated sensor systems for automated damage detection. By developing a combination of ground-based and unmanned aerial systems (UAS) sensor systems, we demonstrate ADA to be completed more swiftly and in a safe, efficient, and cost-effective manner.

Keywords: *Airfield Damage Assessment (ADA), sensor systems, unmanned aerial vehicles (UAVs)*

Background
Critical to the success of all the branches of the Department of Defense (DOD) is the ability to conduct air operations. Air operations do not only focus on air-to-air combat but also support ground and sea operations. Air power includes a variety of roles and responsibilities including air interdiction, intelligence collection, and battlefield management, etc. In addition, the use of air power is not limited to times of war. Heavy use of aircraft is seen outside of war environments such as moving personnel and equipment during peace keeping, humanitarian assistance, disaster relief, and training operations. Regardless of the objective, all aircraft have a basic need for a functional airfield. In a war time environment, not only is this need exceptionally increased, but so is the likelihood that enemy forces will damage our airfields.

Current Navy ADA and ADR processes are dangerous, slow, iterative, and human-in-the-loop dependent. The emergence of cheap, readily available, and accurate technology offers a way to increase the efficiency and accuracy of the ADA process, assist the repair decision making process, and help expedite airfield readiness for take-off and landing operations.

Findings and Conclusions
The goal of this thesis was to develop and test a system architecture and define the data flow to conduct a fast and accurate ADA using a combination of commercial-off-the-shelf (COTS) sensors and equipment. The system we designed and tested utilized a camera-equipped UAV combined with multiple image analysis and processing techniques to assist the Emergency Operations Center

(EOC) in Minimum Operating Strip (MOS) determination and planning of repair operations. We divided the system into two distinct components: initial and secondary runway scans.

The initial runway scan consists of multiple sub components including the UAV flight over the damaged runway, automated damage detection, damage localization, and mosaic creation. The goal of the initial runway scan is to collect and forward the most critical information to the EOC as fast as possible in order to quickly make a determination if the runway is damaged, worth repairing, assist in MOS selection, and visualize, identify, and classify damage to the extent possible. This is accomplished by using survey mapping techniques built into Pix4Dcapture, a Phantom 4 Pro UAV and an iPad/flight controller to take a series of overlapping images across the runway. A trained TensorFlow neural network is then used to automatically identify and classify the damage. This information is both logged for direct output and also visualized onto the image itself. Finally, the images are stitched together and grid lines are placed onto the resulting mosaic using Python's OpenCV library.

The second runway scan takes place after the initial runway scan is finished and an MOS is selected. Once the area that has been repaired has been identified, the UAV can be sent back to previously logged damaged locations and use survey mapping techniques in Pix4Dcapture in order to collect more images of the area of interest. These images can then be used to create 3D models in programs such as WebODM and Agisoft PhotoScan. Finally, the 3D models can be incorporated into existing modeling software such as GeoExPT/AutoCAD in order to estimate required repair materials.

Our system offers a cost-effective and low-training-requirement design that is capable of assisting the EOC in conducting ADA. We divided the system into multiple sub elements including data collection, mosaic creation, automatic damage detection, 3D model creation, and further repair planning analysis. We identified a set of tools and software and tested them resulting in a data flow that produces a mosaic of an airfield, overlays grid lines onto the mosaic, automatically identifies and logs the position of spalls and craters, and generates 3D models for further analysis. These products can have an immediate and direct positive impact on the EOC's ability to conduct ADA by increasing the accuracy and decreasing the time to conduct the assessment. In addition, our system lays the groundwork for continued development and integration with multiple sensors and pieces of technology to create an even more capable solution for automated ADA.

Recommendations for Further Research

Many of the individual components of the presented system design may benefit from further testing, evaluation, and fine-tuning. Regarding placement of the grid lines after the mosaic is created, detailed analysis could be conducted on how accurate the grid lines are based on separate GPS reading of the testing site. In addition, the system would benefit from software based error correction and handing if the mosaic is tilted in order to maximize grid line accuracy. Further experimentation on the optimal drone speed while taking images could have a large effect on the speed of the data collection. Instead of stopping at each waypoint to take an image, it may be possible to orient the camera angle and modify the camera parameters based on the seed of the UAV so that data could be collected faster without sacrificing accuracy or creating distorted images. During mosaic creation, different image stitching techniques could be tested in order to both maximize speed of the image stitch and also determine optimum image percent overlap decreasing time required for data collection. Vast amounts of testing could be done on the TensorFlow neural network including using different models, varying the training data set, and modifying training parameters in order to maximize detection capabilities. In addition, incorporation of unexploded ordinance (UXO) and camouflet detection are a much needed requirement. Testing and evaluation on the effects of detection at different altitudes and lighting, and the accuracy of both UAV GPS and detected damage locations remains an area for improvement. Finally, with the continued advancement of COTS UAVs, conducting real time damage detection on board the UAV may decrease overall evaluation time.

NPS-18-N172-A: Shipboard Laser Analysis: SWAP-C and Operational Capabilities

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Project Summary
With recent advances in solid-state laser (SSL) technology, and the successful testing of the Navy's Laser Weapon System (LaWS) on the USS *Ponce*, Navy leadership has prioritized the deployment of high-energy laser (HEL) systems out to the fleet as soon as possible. Key issues to address are the size, weight, power, and cooling (SWAP-C) requirements for these systems on various ship classes, which will depend upon the laser output power. The goal of this research project was to study SWAP-C and operational performance requirements for the integration of HEL onto Navy ships. The landing platform/dock (LPD) class ships were selected for a study of HEL placement options according to SWAP-C and performance criteria. Additionally, an in-depth physics-based analysis was performed to determine energy storage requirements for an HEL on a Navy ship. This is an important aspect of the overall SWAP-C requirements for an HEL weapon. A model was developed to study the HEL energy usage required to engage a set of threats in different operational scenarios.

Keywords: *laser weapon system, high energy laser, ship integration*

Background
HEL weapons offer numerous advantages over conventional kinetic weapons, including precise, speed-of-light delivery, low cost per shot, adjustable lethality for various damage levels, and an essentially unlimited magazine based on available electric power. Ultimately, HEL weapons could defend against significant threats such as anti-ship cruise missiles. In the near-term, HEL weapons can enhance layered defense concepts for the surface Navy in conjunction with kinetic weapons by addressing close-in targets and the potential threat of unmanned aerial vehicle (UAV) swarms or fast attack craft targets. Laser systems can enhance situational awareness, battle damage assessment, and combat identification using their sensing capabilities. Lasers can also be used for "soft-kills" such as dazzling that can impair sensors and weapon guidance capabilities on adversary assets.

The LaWS tests, which began in September 2014, demonstrated that an HEL weapon system could be successfully deployed and utilized in an operational environment. LaWS utilized commercial off-the-shelf (COTS) fiber laser technology; it operated at a power level of approximately 30 kW with poor beam quality, was not fully integrated with ship power, cooling, and combat systems. The Navy is currently developing newer HEL weapon systems with power levels varying from approximately 60 kW to 150 kW, significantly improved beam quality, and comprehensive ship and combat systems integration. These systems will build upon lessons learned from LaWS. Two major current Navy HEL programs are the Office of Naval Research (ONR)'s Solid State Laser Technology Maturation (SSL-TM) and NAVSEA's Surface Navy Laser Weapon System (SNLWS).

SSL-TM is an ONR-led program to advance laser technologies for future weapon systems. The prime contractor is Northrop Grumman. The near-term goal is to develop a 150 kW class HEL incorporating new technologies such as an off-axis beam director and spectral beam combining.

This system is scheduled for delivery in FY19 on an LPD platform, and will be tested against a variety of targets.

SNLWS was recently designated as an Accelerated Acquisition by the Chief of Naval Operations (CNO) and the Assistant Secretary of the Navy Research, Development and Acquisition (ASN(RD&A)). The goal of this program is to accelerate fielding of laser weapon systems out to the fleet. Program Executive Office Integrated Warfare Systems (PEO IWS) is the Program Office for SNLWS, with Naval Surface Warfare Center (NSWC) Dahlgren as the Technical Direction Agent. The first increment, known as High Energy Laser with Integrated Optical-dazzler and Surveillance (HELIOS), will be a 60 kW class HEL with a counter-ISR (C-ISR) dazzler. The first two deliveries are to be in FY20; one of them is planned for deployment on a DDG51. A key aspect of HELIOS will be ship integration. Future increments of SNLWS are expected to boost power output up to 100s of kW, incorporating technology advances from the SSL-TM program.

As indicated above, the initial deployment of SSL-TM will be on LPD, and HELIOS will most likely be installed on a guided missile destroyer. However, Navy leadership is interested in the feasibility of deploying HEL weapons on a variety of platforms, to address numerous near-term and future threats. HELs may be used to supplement, or in some cases replace, existing conventional weapon systems. This requires a thorough study of the trade-offs between these systems and platform integration issues (including SWAP-C) for HEL weapon systems.

The Directed Energy (DE) Group in the Naval Postgraduate School (NPS)'s Physics Department has been involved for the past 28 years in the design and development of DE weapons, including many of the issues to be addressed in this study, such as required laser output for various engagement scenarios, and the corresponding shipboard power and energy storage requirements. The NPS Systems Engineering Department has significant experience studying SWAP-C issues for naval weapon systems. This collaboration leveraged each department's expertise to address important platform integration issues for laser weapons.

Findings and Conclusions

The team utilized contacts at PEO IWS and ONR to obtain detailed information on current and planned HEL weapon systems for the surface Navy, including HELIOS and SSL-TM, as well as proposed platforms for their deployment. Combining that information with available literature and reports, the team identified operational capabilities based on HEL weapon system performance assessment and defined ship integration requirements (including SWAP-C). The team studied the LPD-class as an example ship platform for laser integration. Evaluation criteria for laser placement on ships included the following: available space, power, cooling, operational coverage, performance, and maritime environment effects. Using laser performance models developed by the NPS Physics Directed Energy Group, the team studied laser performance against different threats based on power (energy) levels available. The team performed two detailed studies that supported an individual master's thesis and a team capstone thesis project.
Study #1 was an in-depth physics-based analysis of the energy storage requirements for an HEL on a Navy ship. This is an important aspect of the overall SWAP-C requirements for an HEL weapon. The energy storage system could end up being a significant portion of the overall size and weight of an HEL weapon. Furthermore, the model developed for this study could readily be modified to examine cooling requirements as well.

Study #2 was a trade-space analysis for integration of an HEL into an LPD class ship, using a systems engineering approach. The study considers various SWAP-C factors, turbulence and environmental effects, azimuthal and elevation coverage, and develops criteria for optimal placement of the HEL beam director onboard an LPD. This significant issue is currently under discussion at Naval Sea Systems Command (NAVSEA) for consideration of HEL deployment on existing and planned Navy platforms. The methodology and results of this study could be extended to inform that decision-making process.

Recommendations for Further Research

A major result of this project is the development of an HEL engagement model that can be used to estimate the amount of energy storage required for an HEL weapon system, given a defined set of targets, HEL parameters, and atmospheric conditions. For the parameters and assumptions that we used, it was determined that a 200 MJ energy storage system would be required. The model was developed for this project could be easily extended to study other SWAP-C issues such as cooling requirements.

The model developed for this project will form the basis for a follow-on project that has recently been funded by ONR. This will be a multi-year, multi-departmental effort to develop an HEL engagement model incorporating various aspects of physics, meteorology, and systems engineering, plus visualization. The initial version of the model will be an interactive "red vs. blue" wargame that will be used to educate and train military officers who attend NPS on the usage and tactics of HEL weapons. A future version will involve an automated mode incorporating machine-learning algorithms to evaluate and develop tactical decision aids for HEL weapons. The model will be used to study various concepts of operations (CONOPS) and SWAP-C issues for HEL weapons, trade-offs between HEL and kinetic weapons, and counter-measures to defend against HELs.

A further result of this project is the development of a systems engineering based approach to evaluate the optimal placement of an HEL beam director on a Navy platform, taking into account ship integration and tactical issues such as azimuth and elevation coverage. For the platform that was studied (LPD 17 class ships), it was determined that the optimal design would be two beam directors, one high on the bridge and the other aft on the port side. Various assumptions were made that could affect this result, but the methodology developed here could be used to modify those assumptions, and to consider HEL placement on other platforms.

NPS-18-N181-A: Integrated Salvo Table

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Project Summary

This study examined the feasibility of an Integrated Salvo Table tool that could help planners understand the most efficient ordnance packages to order, as constrained by availability and delivery method, against given threat packages. We investigated the following questions:

- How can we develop an initial framework for an integrated salvo table as described?
- Is it feasible to develop a comprehensive/integrated salvo table which would operate in Navy Information Technology (IT) environments?
- Is it feasible to network the Table for multiple users in different locations to collaborate?

Existing salvo tables are printed documents that assume the decision maker will choose the target and the type of weapon to be used and that there will be exactly one of each. Given the type of target, the type of weapon, and the desired outcome, the table determines the needed salvo size and how many missiles to launch to achieve the desired outcome. All other aspects of the problem are left to the human decision maker.

As the Navy adopts new ideas such as Integrated Fires and Distributed Lethality, additional concerns become relevant. Both offense and defense may involve cooperation between multiple platforms, both surface and air. It is vital that tactical planners understand how new and advanced surface warfare (SUW) ordnance types can be employed in combination by air and surface launching platforms in order to achieve the desired effects.

Keywords: *Surface warfare, anti-ship missiles, weapon target pairing, salvo, decision support*

Background

Warships can operate independently or in a task group. Independently steaming ships will typically only be concerned with defending themselves and will usually be configured in that way. For warships in a task group, combat systems and doctrine will be configured to support mutual defense. This effort aims to optimize system and sensor performance, mitigate mutual interference, avoid duplication of effort, and create a layered defense in depth, thereby maximizing opportunities to destroy inbound missiles.

Missile defense can be expected to be more effective for cooperating groups than for independent ships. This increased effectiveness is due to coordination, which depends on communication. The advantages of mutual defense can be reduced by measures that directly interfere with effective communication, such jamming, and by indirect measures that include disruptions to positioning, navigation and timing systems such as Global Positioning System (GPS) spoofing (Rogoway, 2017).

The effectiveness and pros and cons of hard kill (sink kill) vs soft kill (mobility kill) involve many factors. Most ships will aim to utilize both techniques in an effort to increase opportunities to defeat the target ("hard kill-soft kill integration"). The mix of techniques to be used is outside the scope of the study. The study assumes that the integrated salvo table has to provide estimated salvo size and composition needed for either kind of attack and that it will be up to the users of the system to decide which technique should be used for which target.

The earliest models of naval warfare described artillery engagements. Since the probability of an artillery hit is low, a large number of shots is expected, and defensive action against bullets is not practical (Wikipedia, 2017), Naval artillery engagements were modeled as a continuous attrition process described by the Lanchester equations (Taylor, 1983). These assumptions do not hold for naval missile engagements. Some important differences between the two include:

- Missiles are typically guided by sensor feedback, and therefore have a significantly higher probability of hitting their target in the absence of defensive measures.
- Missiles can be destroyed by defensive systems before hitting their targets, if they sufficiently can be detected early.
- There is tactical advantage in concentrating missile fire in salvos that arrive almost simultaneously, because this can overload defensive capabilities.
- Missiles can be launched from submarines, ships, and aircraft.

In view of these differences, naval missile combat has been modeled as a discrete process that includes defensive fire, described by the Hughes salvo equations (Hughes, 1995 and Cares, 1990). The original version of these equations was deterministic. Stochastic versions of the model have been developed (Armstrong, 2005, 2011), as well as a version that includes a sequence of missile exchanges (Armstrong, 2014).

Findings and Conclusions

The study explored feasibility of developing a framework for supporting integrated salvo tables in Navy IT environments to provide prioritized ordnance combinations against enemy warships. Five models were developed by students, which were then distilled into one final model by the analysis group. The distilled model was called the One Model. This model combined the strongest aspects of the five models, and incorporated insights from Navy stakeholders, and refinements from a second round of student design and subsequent analysis.

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NPS-18-N186-B: Optical Messaging with QR Codes, Digital Flashing Light (DFL), Signal Flags and Li-Fi Networking (Continuation)

Researcher(s): Dr. Don Brutzman, Dr. Weilian Su, Dr. Tri T. Ha, Mr. Nathan Brown, and Mr. Terry Norbraten

Student Participation: LT Dimitri Paspalaris USN and LT Stephanie Robinson USN

Project Summary

Ongoing Naval Postgraduate School (NPS) research in Network Optional Warfare (NOW) and shipboard light fidelity (LiFi) has shown that light communication has the potential to decouple personnel networking from sensitive shipboard networking. LiFi can also reduce significantly electromagnetic (EM) radiation and Telecommunications Electronics Material Protected from Emanating Spurious Transmissions (TEMPEST) vulnerabilities, thus, lowering probability of intercept as well as interference.

Naval surface warships have typically upgraded onboard lighting systems to utilize light emitting diode (LED) fixtures that are themselves compatible with LiFi networking equipment. However, cable distribution for network data remains quite difficult and even problematic for nontrivial distances. Power line communication (PLC) offers the promise of avoiding separate cabling requirements, if lighting circuits can be adapted to support such networking without interference or impacts with other ship systems.

This project builds on knowledge gained from associated optical signaling work performed by prior Naval Research Program (NRP) project NPS-17-N091-C and related research.

Keywords: *light fidelity (LiFi), power line communication (PLC), Network Optional Warfare*

Background

Ongoing NPS research in NOW showed that optical data communications can reduce vulnerability of surface ships to enemy detection and intercept of radio frequency transmissions. Emerging work in LiFi networking as a replacement alternative for radio frequency (RF) based WiFi networking might provide excellent bandwidth below decks on Navy ships. Use of LiFi aboard ship has the potential to decouple personnel networking from sensitive shipboard networks, with the critical benefit of reducing signal vulnerabilities afloat. LiFi seems well suited to below-decks networking in a cluttered metallic environment. This technology is sufficiently well advanced to merit ashore/afloat prototype experimentation. Testing emerging hardware and software in laboratory contexts as proxies for ships and aircraft can show value in surface fleet scenarios. New Navy-sponsored commercial capabilities may further assist in automating onboard optical signaling paths.

Within the hull, shipboard lighting circuits suggest an interesting path for crew-serving Internet data communications. LED lighting is used to transmit and receive packet data within straight-line visual range of a network access point. LiFi technology is now at an early-adopter experimentation stage that is likely to become a popular commercial capability within two years by coalescing on a new IEEE 802.11 standard. Ad hoc optical approaches are also possible (such as solutions from Torrey Pines Limited) but close examination showed that specialty solutions are not desirable since they are not scalable across the fleet. Shipboard data distribution is conceivable using LED lighting now installed on 120VAC circuits. Standalone tablets with no other links besides LiFi can provide strong information security for potential shipboard use. Primary objective of interior-signaling research is to investigate feasible use of on-board ship 120VAC power lines as a medium to transmit signals.

Laboratory configuration work is able to support multiple ongoing thesis efforts including LiFi/PLC testing, throughput testing, and comparison of product suitability for shipboard usage. First-order measurements of signal noise created by PLC is also ready, though further test equipment will be needed to precisely evaluate product-related TEMPEST vulnerabilities. Noise created by cross-over of shipboard power lines and other high-power circuits that utilize higher voltages may also be significant, showing that multiple open questions remain in this cross-disciplinary problem. To assess future deployment of LiFi networks within ships, multiple commercial LiFi modulators need to be evaluated to determine if they can be used with existing LED fixtures. Work continues towards building recommendations that address practical shipboard upgrades (lighting, transceivers, routing and shielding) to deploy a LiFi communication systems that balances high download and small upload speed. If project sponsorship or a formal program of record is eventually continued, comparison of commercial offerings can ensure scalable long-term delivery as LiFi standards stabilize.

Conduct of Work and Equipment Acquisition

This work involves pursuit of multiple capabilities in tandem: LiFi data communications to computers (similar to WiFi) wireless networking, and power line communication (PLC) in order to enable routing of data traffic from onboard ship light fixtures without requiring additional fiber or wiring connections that might require cost-prohibitive Ship Alteration (SHIPALT) approval.

Multiple procurement difficulties delayed project progress and required more time than allotted.

- Incremental budget funding was postponed in favor of prioritizing a separate project to enable focused staff activity on one NRP project at a time.
- At least two candidate implementations were initially available for further testing. Technical assessments, review of standardization activities, and capability briefings confirmed that pureLiFi was the clear industry leader in this domain. An appropriate sole-source procurement package was prepared to purchase pureLiFi gear for testing.
- Subsequent contracting review by NPS experts determined that the rapid evolution of industry capabilities in this emerging market warranted a competitive bid in order to avoid any possibility of contractual challenge and further delays. Project investigators distilled capability descriptions of interest as best possible to meet formal contracting guidance.
- Three competitive bids were received by NPS. Responsive bids included pureLiFi and another company, VLNComm. The lowest-cost bid by VLNComm was awarded with a correspondingly lower level of developmental features. Equipment receipt occurred just prior to project completion at end of FY2018, precluding detailed testing. Work continues.
- Past work in quick response (QR) codes, digital flashing light (DFL) and signal flag communication open-source software was considered but not pursued further due to prioritization of LiFi efforts.

Several other procurement activities were successfully completed in tandem.

- Purchase of PLC equipment was made using the most cost-effective commercial off-the-shelf (COTS) product available. Somewhat inconsistent standardization or commonality exists in this product domain, and no attempt was made to compare PLC product suitability for shipboard use.
- Separate purchase of example shipboard lighting fixtures and cabling was made by Commander, Naval Surface Forces (COMNAVSURFOR) to evaluate the degree to which existing fleet equipment might be usable or adaptable. This equipment arrived October 2018 and requires custom lab hookups.

Security arrangements with NPS Information Technology and Communications Services (ITACS) have approved a dedicated network tunnel between labs in Spanagel and Watkins Halls so that LiFi-PLC-NAP-routing-NAP-PLC-LiFi tests can be conducted with no possibility of alternative routing paths occurring. NPS now has two labs configured for testing and assessment of LiFi and PLC data communications with thesis research work ongoing.

Findings and Conclusions

- LiFi equipment holds significant promise for shipboard use. Corresponding PLC use can accelerate impact and adoption.
- Many unclassified ship activities can benefit from these capabilities including crew personal network connectivity, unclassified log-taking, training, and qualification.
- Purchased equipment is satisfactory for continued NPS testing and evaluation.
- The rapid pace of commercial LiFi development and diverse variety of PLC/ broadband over power lines (BPL) signaling devices deserve accelerated work and more equipment to determine best solutions for naval shipboard use.
- Practical integration experience and evaluation is needed within an actual shipboard environment in order to properly estimate full-scale deployment costs.
- Although multiple challenges delayed project progress, unfunded work continues by both investigators and their active-duty thesis students.

Recommendations for Further Research

a. Feasibility work on LiFi data communications with PLC is sufficiently advanced to merit integration testing of secure unclassified LiFi links aboard a Navy ship.
b. Further development to improve 120VAC LED lamps for shipboard LiFi use is warranted. Design of existing LED lamps in Navy supply system did not include Lifi or PLC criteria.
c. Security tests afloat/ashore need to include automatic detection of PLC/BPL technologies.

d. NPS should pursue a Cooperative Research and Development Agreement (CRADA) with one industry-leading company simultaneously active in equipment, software, and standards development for the best interests of future navy planning. Given the complexities of the LiFi design space and the often-private nature of industry participation in standards organizations, such work will benefit eventual Navy program to upgrade ship capabilities.

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NPS-18-N378-A: Combined, Joint and Coalition Warfare at Sea—Distributed Maritime Operations (DMO)

Researcher(s): Dr. Jeffrey Appleget COL USA Ret., CAPT Jeffrey E. Kline USN Ret., and Dr. Robert Burks COL USA Ret
Student Participation: Maj Nathan Gulosh USMC, Capt Alex Ryan USMC, LT Elizabeth Bochner USN, LT Joshua Baker USN, Capt Rachel Cline USMC, Capt Matthew Danielson USMC, Capt Nicholas Rice USMC, LCDR Shane Beavers USN, LCDR Ray Cabana USN, LT Kyle Belcher USN, LCDR John Renquist USN, CPT Aaron Devig USA, and Capt Kyle Browne USMC

Project Summary

This research project examined Combined, Joint and Coalition Warfare at Sea in a future Distributed Maritime Operations (DMO) environment for US Fleet Forces Command (USFF). It focused on Fleet Design capabilities and capacities, including a rigorous assessment of Joint and Coalition enabler's key elements of Fleet Design. It includes USFF stretch goals, experimentation hypothesis, identified Joint Capability Area capability, select multi-domain capability and identified leap-ahead technology.

The Winter NPS Joint Campaign Analysis (JCA) class' mini-study of a Western Pacific scenario conducted exploratory employment of technologies under the Fleet Design concept as identified by the USFF sponsor, and provided a gross quantitative assessment of military utility as options for the warfighter against a growing maritime power.

The second phase introduced Fleet Design into the Spring OA4604 Wargaming Applications course. A faculty-advised student wargaming team designed, developed, conducted, and analyzed a wargame that leveraged the factors and parameters, measures of effectiveness and scenarios that were identified by the Joint Campaign Analysis effort.

The third phase of the effort conducted a second look at Fleet Design technologies from phases 1 and 2, along with additional technologies as designated by USFF sponsor. This phase included emerging Fleet Design updates and updated Fleet Design "Stretch" goals.

The fourth phase of this research will be to conduct a second Fleet Design wargame in the Fall (FY19) OA4604 Wargaming Applications course. Using feedback from the first two JCA courses and the first Fleet Design wargame in the spring, this wargame will provide a more in depth examination of emerging Fleet concepts and provide an assessment of Future Fleet Design Attributes and provide an assessment of future Navy capabilities through the lens of integration, distribution and maneuver.

Keywords: *Wargaming applications, Joint Campaign Analysis*

Findings and Conclusion - Winter Joint Campaign Analysis Class:
The Winter 2018 Joint Campaign Analysis class studied the world-wide maritime conflict scenario titled "Maritime War 2030" to support the Warfare Innovation Continuum "Distributed Maritime Operations: Combined, Joint, and Coalition Warfare at Sea" and to support the USFF project titled "Combined, Joint, and Coalition Warfare at Sea—Distributed Maritime Operations. This scenario included conflicts occurring in the South China Sea, rising tensions between Japan and Russian, and a Baltic Scenario with hybrid warfare challenges. The focus of this class' analyses was the South China Sea conflict two years mature. The United States and its allies are fighting their way back into the first island chain by planning to recapture the enemy held Indonesian Island of Natuna Besar.

Students developed distributed maritime concepts for force employment, assessed risk, and provided quantitative military assessments of several emerging technologies, such as the LHA-6 Extended Adaptive Force Package with USMC shore-based missiles. The Marine Corps' amphibious capabilities can provide the naval surface action group (SAG) a decisive advantage in reclaiming sea control in vicinity of Natuna Besar. The LHA-6 provides timely and survivable intelligence, surveillance, and reconnaissance/strike assets that can locate premier enemy platforms to ensure first strike advantage. Anti-ship shore batteries can effectively supplement allied SAG missile engagements enhancing the distributed fight. Bottom line summary is that the force that strikes first with the most ordinance wins and that Marine aviation assets are critical in such an effort.

Background - Spring Wargaming Applications Class:
The Wargaming Applications Seminar assessed how directed modular designs and Dynamic Modularity from the Sea (DMS) can be effectively integrated and employed to regain sea control in a cluttered, constrained, and contested battlespace. A wargame, sponsored by U.S. Fleet Forces Command, was conducted to study three focus areas:

1. Assess specified command-and-control (C2) structures and their abilities to support distributed maneuver in a contested environment.
2. Assess specified modular designs' support to mission execution. Evaluation areas included integration, distribution, and maneuver in accordance with the current Fleet Design Campaign Plan.
3. Identify which current and/or near-future technologies best support mission execution in a contested maritime environment (technologies must meet a time horizon of 2023).

Findings and Conclusions
When fighting in a cluttered and contested environment, expeditionary capabilities must be integrated into modular design. An integrated Fleet Tactical Grid, reinforced by the physical presence of naval forces ashore, restricts enemy options and forces the enemy to invest more time and resources to overt military activities. Ultimately, this reaction helps drive the U.S. diplomatic narrative and places pressure on enemy decision makers.

Distributed, land-based detachments and capabilities reduce the exposure of high value surface combatants, simplify logistic requirements, and allow U.S. forces to better establish a well-integrated Fleet Tactical Grid. Diplomatic efforts will be critical to emplacing the right capabilities in the right places.

Autonomous platforms and expeditionary capabilities increase the agility and robustness of surface modular designs, allowing premier strike platforms greater stand-off from enemy threats. Regardless of modular design, massing physical combat power is difficult, however, massing precision strike capabilities is not. In the Baltic region, advanced basing will be different than what is envisioned in a South China Sea scenario. It is likely that U.S. forces will be capped for diplomatic reasons and integrated with host nation militaries. Thus, U.S. forces should remain light and mobile. Attached equipment must be cheap, expendable, and low-cost in energy consumption.

Findings and Conclusions - Summer FY 2018 Joint Campaign Analysis Class:
The summer 2018 Joint Campaign Analysis class, in coordination with the Tactical Oceanography class, studied a scenario titled "Global War 2030". Global War 2030 includes a Syrian/Israeli conflict which brings both Russia and the United States closer to open hostilities in the Eastern Mediterranean and a similar conflict in the East and South China Sea as describe in the Winter Joint Campaign Analysis course. Concepts and technologies explored included Marine Corps support to DMO, protection of undersea infrastructure, mine warfare in DMO, micro diving swarm unmanned surface vehicles, Sailing Drones, and shore-based anti-ship cruise missiles.

Concept Assessment: Marine Corps support to DMO. In the Eastern Mediterranean scenario, the High Mobility Artillery Rocket System provided significant attrition capabilities against a Syrian landing force.

Concept Assessment: Closing the Mediterranean to Russian Resupply. A combination of mining with sea and shore barriers will be effective in closing the Mediterranean to Russian resupply.

Concept Assessment: Undersea Infrastructure Defense. Traditional mobile platforms (ships, boats, and aircraft) lack the search capability and capacity to effectively defend an extensive undersea pipeline (Natuna oil field pipelines) against an unmanned underwater vehicle attack.

Recommendations for Further Research
The Distributed Maritime Operations and Expeditionary Advanced Basing Operations are two nascent concepts that will require further operations research in order to better understand how the Marine Corps and the Navy interoperate effectively, using these two concepts, to establish and maintain sea control in any maritime environment. These two concepts will need to mature, through continued programs of wargaming and campaign analysis research, to best serve the U.S. Department of Defense.

EXPEDITIONARY ENERGY OFFICE (E2O)

NPS-18-M303-A: Analysis of Connector Usage to Support Amphibious Operations

Researcher(s): Dr. Michael Atkinson, and Dr. Kyle Lin
Student Participation: CPT Matt Danielson USMC, and CPT Coleman Strickland USMC

Project Summary
During an amphibious operation, transporting Marine Expeditionary Unit (MEU) resources from ship to shore is a burdensome endeavor full of risks and complexity. Current scheduling techniques are arduous and time consuming, resulting in inefficiencies in the transition of resources from sea to land. Planners need an effective tool to limit these inefficiencies in an effort to expedite and prioritize the movement of supplies. In 2017, Major Robert Christafore developed the MACS tool to

optimize the delivery of bulk fuel to forces ashore. This project generalizes the models and algorithms underpinning MACS in two major ways. First, we maintain our focus on delivery of one class of supplies (nominally bulk fuel) and extend the MEU Amphibious Connector Scheduler (MACS) model to encompass multiple objectives, weather implications, and reliability considerations. These additions greatly enhance the MACS's ability to account for real world situations. Second, we generalize MACS to multiple commodities. This extension provides amphibious planners with a flexible and versatile planning instrument, which is much more operationally relevant compared to the one-commodity variant. The primary model is a temporal network flow model that generates the number of round trips from the seabase to the shore of various configurations of delivery vehicles. We develop a mixed integer linear program and a linear program approximation to solve this model. Our approach generates several different schedules, which allows the decision maker to tailor the schedule to mission-specific requirements. Through our analysis of complex notional scenarios and a historical case study, we demonstrate the potential of the updated MACS as an amphibious planning tool of the future.

Keywords: *amphibious operations, logistics, optimization, network flow models*

Background

Conducting offensive warfare via amphibious operations involves the landing of embarked ground forces onto an enemy beach. Notable for their speed and element of surprise, these operations are used to secure a foothold in an enemy-controlled area for the rapid buildup of a much larger force for follow-on operations. In this project, we develop models and algorithms that focus on facilitating an amphibious planner's ability to provide sustainment of forces ashore. Specifically, we focus on the transportation of materials from a seabase to shore to meet the supply demands of a landing force operating ashore.

The current planning process remains rooted in foundational methods that differ only slightly from techniques utilized during the Second World War. This research focuses exclusively on the doctrine, tactics, and techniques utilized by the United States Marine Corps (USMC) and United States Navy (USN) to employ and sustain a Marine Expeditionary Unit (MEU) ashore from a seabase. A planning tool to aid the development of effective delivery schedules is critical to the success of the MEU's high tempo operations. The overall objective is to develop a logistics model that schedules the delivery of multiple supply commodities from the seabase to the shore based on a MEU's demand ashore.

This research is a continuation of work accomplished by Major Robert Christafore, USMC, who developed the MEU Amphibious Connector Scheduler to schedule delivery vehicles, called connectors, to transport bulk fuel. The MACS tool produces a minute-by-minute connector schedules for the delivery of bulk fuel from ship-to-shore. The MACS model features three unique sub-models: Quickest Flow, Assignment Heuristic, and Scheduler. We perform two major generalizations of the models and algorithms underpinning MACS.

First, utilizing MACS as the baseline model, we further enhance the tool to incorporate a variety of new constraints providing increased capability and flexibility to the MEU staff. Furthermore, we produce an in depth analysis of the MACS tool to integrate a variety of threat concerns, weather conditions, and maintenance failure rates to analyze how effective the schedules constructed by the MACS tool perform during uncertainties. We then apply techniques to build more robust schedules through the implementation of additional runs.

We next extend MACS by incorporating multiple supply commodities, such as fuel, food, water, ammunition, etc. Our primary quantitative contribution is the generalization of the Quickest Flow Model, which is a multi-commodity temporal network flow that sends supplies from the seabase to shore as quickly as possible. The supply nodes in the network are various connector types, and the demand nodes are locations ashore that require supplies such as beaches, landing zones, and forward operating bases. The final output is a minute-by-minute delivery schedule that routes connectors to various land nodes.

We primarily generalize Christafore 's (2017) Quickest Flow model, which is a temporal network flow model that maximizes the throughput of fuel across all connectors inside a given time horizon. We use the Dynamic Network Flow (DNF) modeling approach from Hamacher and Tjandra (2001) to model the flow of resources throughout our network. Hamacher and Tjandra model the evacuation of personnel from a building utilizing a DNF model with the nodes representing rooms and a super sink node designated as the safety area (Hamacher and Tjandra 2001). Their DNF model creates copies of the static network flow problem and expands these copies over a discrete time horizon.

In his research, Kearns (1994) developed a Simulation Mobility Modeling and Analysis Toolbox (SMMAT) to inform decision makers on the impact weather and distances have on LCAC operations. In research closely mirroring Christafore's, Powell (2002) created an Assault Support Optimization Model (ASOM) to determine the optimal combination of military aircraft needed to support a ground combat element (GCE). Reitter (1999) developed the Sea-Based Logistics Decision Support System (SBLDSS), which mirrors Powell's (2002) work in that it exclusively focuses on sustaining forces ashore via the use of air connectors.

Findings and Conclusions

A. Improvements to One-Commodity Model

This work was the basis of the thesis by Captain Coleman Strickland, USMC. Focusing on the Quickest Flow sub-model only, we introduce an assortment of constraints to better utilize the MACS tool for real-world use. Our Quickest Flow sub-model is a temporal network flow model to measure the amount of resources delivered to shore across a given time horizon. We reformulate existing constraints inside of Quickest Flow to more accurately reflect the movement of supplies across the land network. We implement a fuel constraint to calculate the amount of fuel consumed by the connectors during the course of a schedule, providing the ability to build more fuel efficient schedules. Moreover, we implement a technique to incorporate land node priorities and introduce a constraint to integrate equity across the land nodes. With these additions, the MACS tool is capable of constructing five unique schedules, each with their own particular capability. Furthermore, each of these schedules can be layered to provide a schedule tailored specifically for the user.

We study the effects of uncertainty in our reformulated model through the application of two different analyses: 1) Initial Connector Availability and 2) Intra-Day Connector Failures. Analysis 1 examines the effectiveness of bulk fuel delivery during a MEU deployment, and presents a greater understanding of what the MEU staff can expect to deliver to shore under a variety of unpredictable situations. For this analysis, we construct a set of scenarios and sub-scenarios that we apply to our planning tool. Each scenario features a land network with realistic fuel demands and connector assets. These scenarios create the baseline inputs into our analysis. To incorporate uncertainty we develop a set of sub-scenarios to represent a multitude of weather concerns, threat conditions, and maintenance failure probabilities. Each sub-scenario is then applied to our baseline scenarios to study the effects of uncertainty. Through Analysis 1, we determine the MEU can expect a degradation of 33% of resources successfully delivered to shore on any given day under a variety of uncertain conditions.

Analysis 2 focuses on the implications of maintenance failures throughout the duration of a connector's schedule. This analysis incorporates maintenance failure rates, degradation factors, and repair times to accurately represent maintenance actions during the course of a connector's schedule. Additionally, our analysis constructs additional runs inside of a connector's schedule to increase the likelihood a connector can successfully deliver the required fuel to shore. Our assignment policy for allocating additional runs across the connectors produces a 5% increase in the amount of fuel successfully delivered to shore.

A critical assumption in the MACS model is the expectation the bulk fuel carrying capacities across individual connectors of a given connector type is constant. For example, a landing craft utility (LCU), a common surface connector type, has an inputted capacity of 1,800-gallons; therefore, the MACS model assumes the bulk fuel carrying capacity across all LCUs in the model is 1,800 gallons. This assumption impedes our ability to vary capacities across individual connectors. We implement an algorithm to eliminate this assumption in an effort to provide a tool to calculate an efficient use of bulk fuel container assets across all connectors. Our algorithm successfully finds an efficient assignment of container assets across a multitude of container quantities and connector quantities. Furthermore, the implementation of our container allocation algorithm does not significantly increase the computation time of the MACS tool.

B. Generalization to Multiple Commodities

This work was the basis of the thesis by Captain Matthew Danielson, USMC. In the multi-commodity Quickest Flow model, the main output is the amount of flow of each commodity from the seabase to each land node. A key challenge is converting the flow of supplies in our network to a list of discrete connector runs, each packed with various combinations of supplies. For each connector platform we define several load plans, which we denote as configurations. For example, a configuration of a surface connector called a landing craft, air cushion (LCAC) could consist of a load with 150 personnel, or 1,000 gallons of water and 4 vehicles, or a single Abrams tank, etc. The final output from the Quickest Flow model is the number of runs of each configuration to each land node, such as Beach 1 requires 3 LCAC deliveries consisting of two runs of configuration A and one run of C. We formulate a mixed integer linear program to ensure this final number of runs is integer. We also formulate a linear program approximation that may return non-integer runs. The linear program variant may be preferred for larger problems, when the integer linear program cannot produce a solution in a reasonable amount of time. We develop several rounding approaches to convert the non-integer output to integer runs.

In the objective function of our Quickest Flow model we introduce a term that penalizes the total number of runs. Tuning this parameter generates different schedules that highlight various tradeoffs. This feature allows a user to produce MACS schedules that could favor faster deliveries, or surface over air connectors, or place a greater reliance on the ground network infrastructure. The flexibility this provides is extremely useful for amphibious planners as it allows them to adjust schedules to meet mission specific needs.

Our research demonstrates through multiple examples the versatility and efficiency MACS can provide for sustainment operations by the creation and analysis of several notional scenarios. These demonstrations reflect the flexibility of our algorithms to accurately account for supply compatibility restrictions, vast numbers of configuration permutations, multiple supply commodities, and the ability to accurately produce a schedule of amphibious connector deliveries. Finally, we provided a comparison of our model output against a historical example to demonstrate the improvements MACS can provide to planners for the rapid and accurate development of a ship-to-shore landing schedule.

Recommendations for Further Research

The creation and execution of larger and more complex scenarios into our analysis could provide results that more accurately test the scheduling capabilities of the MACS tool. For example, our scenarios focus on MEU offloads alone; however, the MACS tool has the capability of scaling to larger scenarios such as a MEB. Moreover, the implementation of a variety of connector portfolios will provide the MEU staff expected performance results across a range of connector options for deployment.

More work could be conducted to improve the user interface. In its current form, MACS requires the user to complete 10 separate CSV files and then manually adjust certain starting parameters in Python before running a scenario. Many of these actions could be streamlined into a single Microsoft Excel user interface. This interface could allow a user to input all information required for the generation of the 10 comma-separated values (CSV)s, place them in their folder, update the Python starting parameters, and then run the model in Python. This update would provide the user with a less cumbersome and time-consuming method of running a scenario.

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HQMC Installations and Logistics (I&L)

NPS-18-M103-A: Continued Development of Logistics Simulation System and Application to Personnel and Equipment Attrition in the Logistics Combat Element (LCE) in support of a MEB

Researcher(s): Dr. Joshua Gordis
Student Participation: No students participated in this research project.

Project Summary

The focus of this work is the continued development of a software system for the modeling and simulation of the flow of supplies through a combat logistics network, and the use of this simulation to predict adequacy of the network to meet sustainment requirements on rate of delivery of supplies to ground combat elements. The software will be used to both design the logistics network and to assess the effect of equipment and personnel random attrition rates during the course of the operation. The software simulates the flow of these supplies through the network versus time, and predicts the levels of supplies at all nodes. During the course of the operation, the ability of the network to meet the sustainment requirements on supplies can be jeopardized by the loss of availability (attrition) of both personnel and equipment. This loss of availability can be due to both planned (e.g. routine maintenance) and unplanned (unplanned maintenance and combat-related random events). The logistics simulation will be used to predict the robustness of the logistics network in its ability to meet sustainment requirements with the loss of availability of equipment and personnel. The simulation code is object-oriented, and written in the MATLAB language. The class structure of the code is developed to efficiently represent cargo flow through the network and incorporates stochastic elements which represent the random loss of availability of trucks due to unplanned maintenance.

Keywords: *logistics, simulation, time-domain, stochastic attrition, supply networks, modeling*

Background

The simulation code under continued development for Marine Corps Logistics Operations Group (MCLOG) was originally developed for the simulation of fleet sustainment networks wherein a network of ships and connectors are configured to deliver materiel and supplies to an objective on the beach or inland. The complex problem of modeling and performance simulation of supply networks is addressed by the development of a time-domain simulation tool which allows the user to define arbitrary networks of supply nodes, consumption nodes and logistics capability for materiel movement. The simulation tool allows an arbitrary network to be defined topologically, parameterized (e.g. cargo capacities, transfer rates, speeds, distances, etc.), and both the net throughput and fuel consumption of the network to be calculated. The simulation tool has demonstrated the ability to reveal non-intuitive behaviors of these networks. This program can serve as a real-time tool for designing sustainment networks, responding to changing demand signals from operators, assessing choke-points or factors limiting the throughput performance of the network, and evaluating potential investment in improved systems and technology with the goal of maximizing network performance for dollars invested.

The focus of this work has been the continued development of the software system for the modeling and simulation of flow of supplies through a logistics combat network, and the use of this simulation to predict adequacy of the network to meet sustainment requirements on rate of delivery of supplies to ground combat elements. The software will be used to both design the logistics network and to assess the effect of equipment and personnel random attrition rates during the course of the operation. The Year 1 effort has produced a software simulation system which is capable of modeling a network of ground nodes (logistics elements) connected by "connectors" which typically are a set of trucks, but could also be air or sea vehicles. The objective node is the ground combat element (GCE). The GCE and the intermediate nodes have a requirement that the various supplies required for the mission (e.g. fuel, water, ammo, food) never fall below user-specified levels. The software simulates the flow of these supplies through the network versus time, and predicts the levels of supplies at all nodes. Currently, the software requires as input a large number of planning factors, such as the number of ground nodes, the distance between them, the number and speed of trucks moving between nodes, the loading and unloading rates for the trucks, and the rate of consumption of supplies by the nodes. During the course of the operation, the ability of the network to meet the sustainment requirements on supplies can be jeopardized by the loss of availability (attrition) of both personnel and equipment. This loss of availability can be due to both planned (e.g. routine maintenance) and unplanned (unplanned maintenance and combat-related random events). The logistics simulation will be used to predict the robustness of the logistics network in its ability to meet sustainment requirements with the random loss of availability of equipment and personnel.

Findings and Conclusions

The fundamental questions addressed by this phase of the research are: (1) What are the effects of personnel and equipment attrition to Logistics Combat Element (LCE) mission success in support of the Marine Expeditionary Brigade (MEB)'s execution of Operation Assured Resolve? (2) Given random variances in the planning factors, what is the probability of success to the MEB LCE sustainment mission using simulation? The simulation code under development will address these basic questions. At this interim, two major enhancements to the simulation code are complete, and near complete. The first enhancement was the implementation of convoy operation. Prior to this enhancement, the code represented individual trucks, each carrying a mix of supplies. On average, this was able to represent the overall supply network performance. The code was significantly modified to represent convoys of trucks, where each convoy is a user-specified mix of different truck types, each truck of a specific type for the cargo it carries. The representation of movement went from moving the individual trucks to the movement of convoys. This required a major redesign of how to schedule and deploy these assets. For example, rather than simply loading up and deploying a sufficient number of trucks (as soon as they are available) such that storage capacity at the receiving node is not exceeded, the loading of convoys is scheduled on-demand. A key aspect implemented is the amount of cargo to be delivered by the convoy is calculated as the capacity of the receiving node less the current amount of cargo on hand at the receiving node. The code also now includes a user-specified "order point," where the deployment of the loaded convoy can be scheduled in advance of cargo dropping below user-specified minima at the receiving node.

The implementation of stochastic attrition is near completion, and preliminary results show that the simulation captures the effects of attrition. A given network design, with no attrition, may meet all sustainment requirements (supply levels never falling below user-specified minima) but with stochastic attrition, may not meet the requirements.

The logistics simulation requires numerous planning factors in order to design the network. For example, a supply node delivers supplies to a GCE via a number of trucks in a convoy. The number of trucks, their capacity (max load), and their speed are planning factors which impact the ability of the network to meet the GCE sustainment requirements on supplies. The attrition of equipment (loss of availability of trucks) can be modeled to assess the effect on sustainment, and compensatory adjustments in other factors can be considered to ameliorate the effect of the loss of availability of trucks. The attrition of personnel that operate equipment and trucks can be modeled to assess the effect on sustainment, and compensatory adjustments in other factors can be considered to ameliorate the effect of the loss of available personnel to operate the equipment. The objective is to perform simulations with these unplanned attritions in a logistics network in order to demonstrate the use of the software for the design and evaluation of these networks in support of a Marine Expeditionary Brigade.

At this point in the research, much has been learned about how to build a simulation code for supply networks with stochastic attrition. The attrition required the implementation of more advanced time keeping (day – hour – minute) as opposed to the prior fractional hour. The number of trucks in a convoy changes with time as individual trucks move in and out of different maintenance levels. Practically, at the current level of fidelity, a truck is considered either operational or non-operational. Trucks in intermediate levels of maintenance have some probability of returning to operational status, but also may move to a permanent non-operational status. A convoy is either at the sending node (loading), transiting to/from the receiving node, or is at the receiving node (unloading). The stochastic attrition generates, each day, a random time of day for each truck to possibly change maintenance level. The change from the current maintenance level to a different level is probabilistic, based on combat planning factors which are associated with a Markov chain model for maintenance level state change. If a truck changes to a non-operational status, its cargo is assumed lost.

Recommendations for Further Research

Much work remains to improve the fidelity of the simulation as well as the usability of the code.

- Arbitrary network topologies: The code is already built-in for arbitrary topologies, but the logic for on-demand convoy deployment was added recently and hence this needs to be validated and the code updated if necessary.
- Build new input file structure: Current input file uses same format for static nodes (e.g. supply nodes) and dynamic nodes (e.g. support truck convoys). Revise input format so that static and dynamic nodes have distinct formats.
- Build new plotting module: Currently, plotting module only supports the Operation Assured Resolve topology (e.g. three static nodes and two dynamic nodes). A new module would allow plotting of an arbitrary number of nodes.

- Robust error trapping: Only rudimentary error trapping is implemented as the focus was on demonstrating functionality.
- Increase number of Truck Types: Currently there are only one truck type per supply item (e.g. a single type of fuel truck carries fuel, etc.). There are various ways to handle additional truck types. The most general way is to read an excel spreadsheet which has a library of truck types with the associated parameters (cargo capacity, fuel capacity, fuel consumption, nominal average speed, etc.). The user would then select the truck type and number to assign to convoys). Also, include non-load carrying trucks, such as wreckers and support trucks.
- Refined truck load-out: Currently, trucks are loaded until their capacity is reached in terms of the number of selected units, e.g. gallons, pallets, etc. Revise code to allow trucks to be loaded until capacity constraint is met on either number of units (existing capability), square foot of cargo area, cubic foot of cargo area, etc.
- Moveable nodes: Some “static” nodes should have the ability to change position. For example, a GCE node moves at certain times. Include the ability for the user to specify position versus time for each static node.
- Refined logistics operations: Include additional features in attrition such as the retrieval of inoperable vehicles, no-go conditions, retrieval of cargo on non-operational trucks, etc.
- Interface with other USMC software: Receive input from, send output to other logistics software.
- Restructure/Rewrite Code: Through the development of the code, the concepts and techniques developed to represent logistics simulation have been developed and evolved. The code is written in MATLAB, and is an object-oriented code. The class structure of the code was developed to represent the topological and dynamic characteristics of the logistics operations. The addition of attrition, and further enhancements which may be pursued, has introduced further complexity which calls for certain modifications and additions to the class structure. This would not only improve run-time efficiency, but make the code more maintainable.

NPS-18-M319-A: Improving Marine Corps Logistics with Model-driven Big Data

Researcher(s): Dr. Susan M. Sanchez, Dr. Thomas Lucas, LtCol Mary McDonald USMCR, and Maj Stephen Upton USMC Ret.
Student Participation: Capt T. Patrick McKavitt USMC

Project Summary

The Marine Corps Logistics Command (MARCORLOGCOM) uses complex computer-based models to help manage the Corps’ materiel. These models help MARCORLOGCOM better understand the potential impacts and risks that operations and changes in policy may have on various units’ sustainability and readiness. This research improves upon the ability of MARCORLOGCOM analysts to quickly and efficiently obtain experimental information from their Repair Optimization Materiel Evaluator (ROME) model using data farming. ROME is used annually to assist in planning depot-level maintenance for ground support equipment given constrained resources. The Marine Corps depot level maintenance budget for fiscal year 2019 is projected to be nearly $350 million, which meets only 80% of the operating force’s requirements. Thus, maintenance choices must be made that will impact on unit readiness.

In this research project, the Simulation Experiments and Efficient Designs (SEED) Center has built, tested, and documented software that enables data farming with ROME. That is, ROME has been embedded in an environment that facilitates massive experimentation using cutting-edge experimental designs. This new capability has been tested with some initial experimentation. A PowerPoint presentation serves as an initial documentation of the results of those experiments.

Many results seemed intuitive, well-explained, and generally support model verification and validation. However, there are also a number of findings that we found counter-intuitive. Further investigation, in collaboration with ROME with model users, is ongoing. This investigation has also advanced our ability to data farm by improving the quality and speed with which we can glean insights through experimentation with ROME or other computational models.

Keywords: *logistics, maintenance scheduling, simulation, design of experiments, data farming, big data, Repair Optimization Materiel Evaluator (ROME).*

Background

MARCORLOGCOM uses models to ensure that Marine Corps units are efficiently equipped and their equipment is well maintained. Complex simulation models are used when physical experimentation is not feasible or is cost prohibitive and simple closed-formed approximations are inadequate (Lucas et al., 2015). Some of these models contain a large number of input variables, many of which are uncertain (e.g., the demands and breakdowns rates for many diverse parts in future operations). They also generate an enormous amount of output data, including multiple responses of interest (e.g., cost, availability, and readiness over time).

There have been dramatic recent advances in the science of being able to explore such models (see Kleijnen et al., 2005). The enabling technologies are high-performance or cluster computing, design of experiments, data analysis and visualization, and software scripts that enable data farming. Within the SEED Center for Data Farming (http://harvest.nps.edu) at the Naval Postgraduate School, faculty and students routinely run thousands of experiments on computer clusters while simultaneously varying scores of input variables. SEED is an acronym for simulation experiments and efficient designs. Over the last decade, the SEED Center has embedded over a dozen Department of Defense models in data farming environments.

The computational model chosen to be made data farmable for this effort is MARCORLOGCOM's Repair Optimization Materiel Evaluator (ROME). ROME is a decision support tool that is used annually to assist in building an equipment repair list for serviceable ground support equipment. ROME uses a deterministic mixed integer program to maximize a readiness measure subject to numerous constraints, including cost. Given hundreds of inputs from the Marine Corps' Master Data repository, some of which are uncertain, and equipment warfighting values, ROME generates a detailed equipment repair list and schedule that "optimizes" overall readiness. Of course, the goodness of the solution depends on the accuracy of the input data as well as multiple subjective assessments. Therefore, it is important that robust solutions are obtained.

Findings and Conclusions

To improve upon MARCORLOGCOM's ability to create depot-level maintenance schedules in a fiscally constrained environment, the SEED Center has built, tested, and documented software that enables data farming with ROME. That is, analysts can now automatically run and analyze thousands of experiments in ROME while efficiently varying numerous inputs. This new functionality has been used in a pilot analysis on a subset of the overall equipment (i.e., focusing on only a portion of the 207 items in the Table of Authorized Material Control Numbers (TAMCNs) in ROME's input data files.

The data farming software has been developed, tested, and implemented using python3. This prototype software has been named ROMEfarmer and is run using the command line. ROMEfarmer takes (1) a user specified designed experiment (DOE) instantiated in a comma-separated values (CSV) formatted file, (2) a set of ROME input files, and (3) necessary General Algebraic Modeling System (GAMS) optimization files, then runs the designed experiments in parallel on a single machine using all available cores.

In addition to developing the ROMEfarmer software, we also investigated other statistical analysis techniques that might advance our ability to data farm by improving the quality and speed with which we glean insights through experimentation (Erickson, Ankenman, & Sanchez 2018).
We initially tested the functionality of ROMEfarmer using a small sample DOE (three design points), then with a little bit larger DOE (17 design points using a nearly orthogonal Latin hypercube). This established that ROMEfarmer worked as intended. We then used the new capabilities to conduct an initial data faming analysis on ROME. Our purpose was to (1) test the mechanics of the data farming architecture, (2) begin to explore the sensitivity to selected inputs, and (3) assess the impacts of broad sweeps and boundary testing.

Many results seemed intuitive, well-explained, and generally support ROME model verification and validation. For example, since cost is a constraint and not an objective, the allotted budget was always close to fully expended. Additionally, the objective value (surrogate for readiness) generally increased as budget was increased. Further, in the broad sweep on the inputs for 10 TAMCNs, the influence of the inputs on number of parts to be repaired, by type and in period, was largely consistent, and the directionality of the main effects made sense. For example, increasing war material requirements and unserviceable returns that are forecast to occur tended to increase the number that should be repaired; and increasing cost tended to decrease the number to repair. However, there were also a number of findings that the team found counter-intuitive or surprising. It is certainly possible that good reasons exist for these findings, and therefore do not necessarily indicate a ROME issue. Nevertheless, at this point they seem to merit further investigation involving ROME users and subject matter experts. One key finding suggests that data farming may help identify plans that substantially reduce depot maintenance costs without little adverse impact on readiness. These findings were documented in a brief and letter delivered to MARCORLOGCOM.

To facilitate ROMEfarmer's use by MARLOGCOM, a draft user's manual has been written (SEED Center 2018). In addition, a prototype VBA code Excel front-end has been added to ROMEfarmer to make it easier to use. Finally, code has been developed to parse and extract selected ROME output in a format suitable for analysis. This new capability is called ROMEminer.

Recommendations for Further Research

New capabilities have been created and tested that enable ROME analysts to efficiently conduct massive experimentation with ROME to better understand the high-dimensional maintenance plan trade-space. The question remains, what will MARCORLOGCOM do with these new capabilities? At a minimum, they can interact with Captain Pat McKavitt to drive his experimentation and analysis using ROME with a goal of affecting their stakeholder meetings. However, if time and resources are available, we recommend that MARCORLOGCOM sponsor a workshop involving the SEED Center, ROME users at LOGCOM, and maintenance planning experts. During this workshop, the group will iteratively run and analyze a series of ROME experiments. The SEED Center will also provide a short course on how best to use the new data farming capabilities in ROME. This will ensure that the expanded analysis power of ROME is transferred to analysts resident in Albany, GA. Ultimately, we recommend that MARCORLOGCOM formally integrate the new ROME data farming capabilities into their Master Scheduling Support Tool (MSST).

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HQMC Manpower and Reserve Affairs (M&RA)

NPS-17-M057-A: A Matched Retrospective Cohort Study of Career Outcomes of Sexual Assault Victims

Researcher(s): Dr. Lyn R Whitaker and Dr. Andrew T. Anglemyer
Student Participation: LTJG Amanda Benavides USN

Project Summary

Sexual assault in the United States Marine Corps remains high in the list of priorities and at the forefront of public concern. To better understand and combat the issue, our work examines how career outcomes for Marines who filed a formal unrestricted report of sexual assault, case Marines, differ from those who never filed a report, control Marines. Additionally, we evaluate whether career outcomes for Marines who filed a formal unrestricted report of sexual assault differ based on key demographics. Enlisted Marines of ranks E-1 through E-4 who filed unrestricted reports from 2011 to 2015 are matched by age, rank, gender, Military Occupational Specialty (MOS), and report date to Marines who have never filed an unrestricted report. Using logistic regression analysis, career outcomes are measured by separation status and narrative within one year from the sexual assault report date. Results reveal that in general, case Marines are more likely to separate, and separate for reasons other than end of contract than their control Marine counterparts. Variables such as rank, occupational field, number of dependents, and average professional and conduct scores (PROCONS), class, and change are contributing variables.

Keywords: *sexual assault, Marine Corps*

Background

Sexual assault in the United States military is a widely publicized and highly prioritized issue. Despite the military's "zero tolerance" policy (Downes, 2013), it remains a pervasive and contentious problem. The Marine Corps and the Sexual Assault Prevention and Response Office (SAPRO) sponsored this work (funded and administered by the Naval Postgraduate School (NPS) Naval Research Program (NRP)). We wish to acknowledge and thank Dr. Marcon Zabecki and Mr. Eric Lockmer of SAPRO for facilitating this work and their extensive data collection efforts. SAPRO's aim is to seek a better understanding of career outcomes of sexual assault victims in the Marine Corps. To do this, two questions guide this research.

- How do career outcomes for Marines who filed a formal unrestricted report of sexual assault differ from those who never filed a report?
- Do career outcomes for Marines who filed a formal unrestricted report of sexual assault differ based on key demographics?

Here we provide a summary of our work whose details are found in the NPS Operations Research master's thesis of LTJG Benavides (2017). Benavides (2017) has a literature review, details of experimental design, data collection, data manipulation, analysis, and findings.

Sexual assault affects victims in numerous ways, generally organized into four categories. First, victims often experience mental and psychological disorders such as depression, insomnia, anxiety, or PTSD. Second, victims may endure physical consequences such as sexually transmitted illnesses, pregnancy, or increased abdominal, muscular, joint, and sexual pain. Third, victims' personal and social lives may suffer when their relationships and interactions with people change as a result of the assault's violation on personal rights and boundaries. Fourth and lastly, victims may endure career or professional retaliation from coworkers and supervisors for reporting. Additionally, the combination of negative mental, physical, and personal effects could detract from a victim's professional performance and motivation. When considering the literature and previous research regarding military sexual assault, the evidence suggests that Marines who file formal unrestricted reports of sexual assaults will have poorer career outcomes than Marines who do not. Additionally, the literature indicates possible key demographics such as gender, rank, education levels, and relationship to the subject for propensity of sexual assault and its consequences.

Findings and Conclusions

In response to the guiding research questions, our work compares the career outcomes between Marines who filed unrestricted reports of sexual assault from 2011 to 2015 to similar Marines who have no history of filing a report. Career outcomes are measured in two ways: first, whether a Marine separated within one year of the report date, and second, if a Marine chose to separate, whether the separation was for end of contract or any other narrative. Data regarding the sexual assault was extracted from the Defense Sexual Assault Incident Database (DSAID); data regarding the Marine was extracted from the Total Force Data Warehouse (TFDW). Marines who filed unrestricted reports are referred to as case Marines. They are matched to their control Marines by age, rank, MOS code, and gender at the sexual assault report date. By definition, control Marines do not have a history of filing unrestricted reports of sexual assault, and it is assumed they have never filed a restricted report. As a result, all data for control Marines originates from TFDW only. Two sequential sets of two logistic regression models are applied to the data, for a total of four models.

The first set of logistic regression models is applied to all case Marines, including those who failed to match. The dependent variable for the first model, Model 1, is whether a Marine separated or stayed active duty one year from report date. The dependent variable for the second model, Model 2, is whether a Marine who separated within the year separated for end of contract or any other separation narrative. Independent variables describe the sexual assault, such as the involvement of alcohol, drugs, or weapons and whether a military protection order was issued, and the Marine, such as number of dependents or change in PROCONS from pre to post-incident.

The results of Model 1 and 2 analysis indicate predicated probabilities for staying active duty one year from report date are highest for case Marines with positive change in PROCONS and lowest for unknown change, regardless of rank, involvement of alcohol, drugs, or alcohol, number of dependents, or average pre-incident PROCONS class. Furthermore, predicted probabilities for separated case Marines having end of contract separation narratives are highest for no change in PROCONS and lowest for negative or unknown change, regardless of rank, report year, race, or Marine Air-Ground Task Force (MAGTF) element.

The second set of logistic regression models is applied to both case Marines, excluding those who failed to match, and their control Marines. Model 3 is analogous to Model 1 and Model 4 to Model 2 in regards to the dependent variable. The independent variables remain the same as well, excluding variables that describe the sexual assault since control Marines by definition do not have data for such variables. A binary variable differentiating case from control Marines is also added. The analysis results indicate there is a significant difference between case and control Marines' career outcomes. Marines who reported a sexual assault are much less likely to remain active duty one year after report date than Marines who did not report sexual assault. Similarly, Marines who separate within one year from their sexual assault report date are more likely to separate for reasons other than end of contract than comparable Marines who have not filed a report of sexual assault.

Recommendations for Further Research

There are opportunities for future work regarding career outcomes of sexual assault victims in the Marine Corps. Future work could incorporate restricted reports, match on additional variables, or pursue a survival analysis model. Further, matching cases with non-cases is a promising approach to studies of this type, but the data extraction burden is quite complex and time-consuming, thus we recommend that the matching be done by the researchers and not by SAPRO.

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NPS-18-M222-A: Intangible Benefits in the Composition of the Marine Corps

Researcher(s): Dr. Marigee Bacolod, and Dr. Chad Seagren Maj USMC Ret.
Student Participation: Maj J. Jake Dove USMC, Capt Brian Richmond, Maj Angela Zunic USMC and Capt Viviana Kim USMC

Project Summary

Women comprise approximately 8% of the active component in the Marine Corps, a number less than half of female representation in other military services. While the Department of Defense's (DoD's) recent mandate to fully integrate women is not the focus of this project, the policy dramatically increases the set of opportunities the Marine Corps can offer to women. This project seeks to provide a foundation to ultimately help determine the "optimal" number of women in the Marine Corps.

In particular, we determine what a feasible level of gender integration could look like by creating an empirically justified upper bound of female representation across Marine Corps occupations. To establish this, we develop a mapping of Marine Military Occupational Specialties (MOS) to its civilian equivalents using detailed job descriptors. We find previously male-only Marine MOS are equivalent to primarily male-dominated civilian jobs, where the proportions of women still sit at or below five percent. There is substantial variation in female representation across Marine jobs; however, for example, women comprise more than 25 percent in the Manpower/Admin Occupational Field (OCCFLD). The analysis reveals the occupational segregation in the Marine Corps closely mirrors that of the civilian labor market.

Because some Marine jobs do not map well to civilian equivalents, we also examine determinants of success at infantry training. Finding that physical ability is the dominant predictor of success, we use physical fitness data of male and female civilian youth to further estimate the proportions of women we may expect in the infantry OCCFLD. Finally, we develop an analytical framework that can address the costs and benefits of increasing the proportion of women in the Marine Corps.

Keywords: *gender, integration, recruitment, female Marines, occupational specialties*

Background

When the combat exclusion for women in the military was lifted in 2016, the new policy made 54,000 billets - approximately 1/3 of the entire Marine Corps Table of Organization - available to qualified women. In addition, 32 previously closed primary Military Occupational Specialties and 16 additional Military Occupational Specialties were opened to women. While the change in the combat exclusion policy is not the focus of this project, the policy change has dramatically altered the nature and quantity of the opportunities the Marine Corps can offer to women. In light of these changes it is necessary for the Marine Corps to assess the current status of women in the corps, anticipate how the roles female Marines fill may evolve over time, and determine the extent to which resources should be used to shape that evolution.

Women make up approximately eight percent of the active component of the Marine Corps, a number well less than half of the proportion of women in the other military services. Currently, the Deputy Commandant for Manpower and Reserve Affairs has no tools at his disposal to assess whether eight percent is too many or too few. One can imagine a wide array of benefits that additional women would bring to the Marine Corps. However, given the unique challenges that life as a Marine offers, it is also the case that Marine Corps tends to draw recruits from a vanishingly small pool of qualified and interested candidates.

Our research goals are three-fold:

(1) Build a crosswalk between civilian occupations and equivalent Marine jobs, and, under the hedonic approach, econometrically determine feasible upper bound of proportion of women in Marine occupational fields.
(2) Because some Marine combat occupations do not map well to civilian jobs, determine the factors that predict success at schools that comprise Infantry Training Battalions and use this to predict proportions of women in these occupational fields.
(3) Develop a cost-benefit analytical framework for thinking about an "optimal" number of women Marines.

As such we intend for our research to provide a point of departure from which the Marine Corps may ultimately determine the "right" number of women in the Marine Corps.

Findings and Conclusions

To address our first research goal, we begin by relating each job specialty in the Marine Corps to its civilian equivalent. We turn to two data sources: a website called My Next Move for Veterans (MNMV) developed by the U.S. Department of Labor to aid military service members transitioning into the civilian labor market, and the Occupational Information Network (O*NET). Occupational data in the O*NET are the result of comprehensive studies of how jobs throughout the U.S. economy are performed, including the required knowledge, skills, and abilities required for job performance. Data from 2000 to 2017 on gender concentration for each civilian Standard Occupational Classification (SOC) code come from the U.S. Census Bureau, while the equivalent data on Marines come from the Total Force Data Warehouse (TFDW). For consistency in analyses over time, we also referenced the U.S. Marine Corps MOS Manual as some Marine job titles were reclassified, merged, or deleted. Using data of detailed job descriptors from MNMV, O*NET, the MOS Manual, and prior literature, we develop a crosswalk of Marine primary military occupational fields (PMOS) to its civilian equivalents (SOC). Major Angela Zunic's master's thesis supports these efforts.

Mapping Marine MOS's to its equivalent SOC, Zunic (2018) finds a very heavily male-dominated civilian sector for equivalent Marine occupations. Specifically, the previously male-only Marine occupations in combat arms are largely equivalent to civilian occupations such as firefighting, where female representation currently still sits at or below five percent. This highlights the occupational segregation across civilian labor markets, indicating a low supply of female workers choosing to be in or being hired for such jobs. Meanwhile, there is substantial variation in these occupational comparisons. For example, the 31xx Distribution Management Marine OCCFLD have similar gender representation (26%) with its civilian equivalent of Logisticians. In contrast, the 01 Manpower and Administration OCCFLD has 25% female while its civilian equivalent, Human Resources, is 80% female.

Suppose we assume that the civilian labor market is sufficiently close to an equilibrium, where men and women have sorted into occupations that best utilize their skills and abilities for which they get the best possible reward. Under this hedonic assumption and using the occupational crosswalk, we can then develop an econometric model where we regress representation on multiple job characteristics such as skills, abilities, and knowledge required for job performance using data from the O*NET. The coefficients on these regressors have the interpretation as the marginal proportion of women for a one-unit change in that job characteristic. Knowing what the detailed job descriptors of Marine OCCFLDS are, we can then predict the proportion of women for each OCCFLD.

Next, we recognize that the O*NET database may not map well to some Marine occupational fields, particularly occupations in the combat arms. Of course, the combat arms comprise the very occupations that have just opened to women, so there is also a lack of institutional experience with respect to the performance and retention of women in those fields. To mitigate this gap, we examine the determinants of success at the schools that comprise the Infantry Training Battalions (ITB). The thesis by Major John "Jake" Dove and Captain Brian Richmond supports these efforts.

Dove and Richmond (2017) find that physical health and performance account for almost 80 percent of failures at the Marine Corps' ITB. Using data from several cohorts of enlisted Marines that attended ITB-West and ITB-East, logistic and multinomial logistic regression model estimates show that by and large physical abilities—as measured by performance on constituent events in the physical fitness test (PFT), combat fitness test (CFT), and rifle scores—are the largest predictors of success. Some dimensions of cognitive ability also matters, while characteristics such as height and weight have nonlinear predictive effects.

Our project's final effort is to devise a way to think about the benefits and costs the Marine Corps may experience as they attempt to increase the number of females on active duty. Captain Viviana Lee's thesis attempts this by examining the implications of integration on recruiting and readiness.

In particular, Lee (2018) examines aspects of recruiting females into the infantry MOS, extending the findings by Dove and Richmond (2017). She turns to data from the California Department of Education (CDOE) of California high school students' measures of physical fitness equivalent to the constituent events in the Marines' PFT (i.e., pull-ups, crunches, mile run). These physical fitness outcomes are for the population of ninth graders in the state of California during the 2016-2017 school year. One limitation of this data is that 9th graders are typically 14 to 15 years old, when we'd ideally like to observe performance of 17 year olds. Using the CDOE dataset and estimates from the predictive model using the ITB data that Dove and Richmond (2017) developed, Lee (2018) finds that the expected probability that the average 9th grade male graduates from ITB is 0.89, while only 0.17 for the average female in the CDOE data. On the other hand, analysis of CDOE data shows some evidence in favor of the idea that young females capable of becoming Marines and attaining Marine physical standards are higher in the quality distribution of their gender relative to young males.

Imagine the pool of male civilians from age 18 to 26. Suppose we were to rank those individuals with respect to their quality or their ability to not only earn the title "Marine" but succeed in their first term of enlistment. We are likely to find that the marginal Marine, that is, the Marine who barely succeeds at basic training and/or their MOS school, but then goes on to perform adequately in their first term, is found at or about the 30th percentile of this distribution. It is important to ponder this recruit's alternatives to joining the Marine Corps. Given his position on this distribution of quality, it is unlikely he is heading to a four-year college. Anecdotally, and given his comparative advantage, we might imagine him as working construction over the summer and will start community college in the fall.

Now instead consider the same quality distribution for female civilians age 18 to 26. Given the physical rigors of Marine Corps entry and training, the marginal female that signs up for a traditionally open MOS (i.e. administrative clerk, logistics, etc.) is likely to be in the 50th or 60th percentile of the quality distribution. Since entry into combat arms MOS is even more physically demanding than non-combat arms MOS, the marginal female capable of succeeding in ITB is likely to be substantially higher on the quality distribution than her non-combat counterpart. It is reasonable to suppose that the marginal female combat arms recruit is a very good athlete relative to her female peers and perhaps has opportunities to play sports in college. She may even have an athletic scholarship.

Such a scenario is in theory, of course, the conditions for which we discuss in more detail in our paper. Findings by Lee (2018) using CDOE data provide suggestive evidence consistent with the scenario. Thus, in order for the Marine Corps to think about costs and benefits of accessing additional females, it must compare the intensity of effort and resources to expend to recruit females in comparison to males, while balancing against relative benefits. A full treatment of benefits would likely require a rigorous structural analysis to appropriately estimate the value of the work the additional women would provide the Marine Corps. For example, one possible method would be to use the value of the candidate's next best civilian alternative as a measure of the value of their work. Such an analysis is beyond the scope of this current effort, however.

What we instead examine on the benefits side are the likely implications of integration on force readiness. Lee (2018) uses TFDW data from 2009 to 2017 to examine the extent to which males and females differ in maintaining a deployable status and how deployability by gender varies across MOS. The purpose is to get a sense of the manner in which Marines of different genders and occupational specialties contribute to the production of combat effectiveness. While the status "deployable" is an imperfect metric for a Marine's productivity, one could argue that Marines who are *deployable* are able to contribute more directly to the organization's ability to produce combat effectiveness; they are ready to be called to perform relevant operational duties. Lee (2018) finds that on average females are less deployable than males during the first four years of service, with the differences peaking during months 25-36, with the major cause of a female's unavailability being pregnancy.

Recommendations for Further Research

We recommend further research on constructing an MOS to SOC crosswalk. This can be done using survey instruments administered to Marines in those particular jobs, inquiring on the particular skills, abilities, work styles, work content, and others, for job performance. Such an enhanced crosswalk would be valuable for determining the next best opportunities for Marines in the civilian labor market, which in turn can answer multiple manpower planning policy questions.

We are also in the middle of incorporating additional data on propensity to enlist in the Marines, estimated over the U.S. youth population, as a way to more clearly identify gender differences in recruiting effort intensity.

Since our analysis reveals injuries were a substantial reason for failure from ITB, we also recommend a more focused study on the determinants of injuries at ITB.

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HQMC Plans, Policies & Operations (PP&O)

NPS-18-M336-A: Analysis of Non-lethal Directed Energy Weapon Employed in an Area Denial Mission Scenario

Researcher(s): Dr. Wayne Porter, CAPT USN Ret., Dr. Eugene P. Paulo, and Dr. Paul Beery
Student Participation: Mr. Alfredo Betancourt CIV, Cao Chung, LT Bryce Hadley USN, Mr. Benito Perez CIV, and Mr. Trevor Scott CIV

Project Summary
The operational threat environment is becoming more complex and uncertain as threat capabilities materialize and re-emerge from near-peer military competitors. A need for increased mission effectiveness, against a dynamic and technologically equal adversary, requires the development of new capabilities to defeat these emerging threats. Those uncertainties extend to the United States and regional security partners that may be susceptible to amphibious attack resulting in the need for an Operational Littoral Defense System (OLDS). Strategically significant amphibious operations will play an increasingly critical role in the projection of power and control in battle-space environments. OLDS attempts to deter, disrupt, and deny enemy forces from completing their amphibious operation. Non-lethal weapons (NLW) systems that are currently in service and/or under development by the Department of Defense (DoD) Joint Non-Lethal Weapons Program (JNLWP) are employed within OLDS and utilized in conjunction with lethal weapon systems to support defensive operations of an amphibious operating area by increasing lethality, reducing potential casualties, and increasing mission effectiveness. This study of NLW systems within OLDS addressed the impact of NLW systems in a traditional conflict scenario, provided insight to potential operational capabilities enhanced by NLW, and analyzed potential effects to lethality, survivability, and mission effectiveness.

Keywords: *non-lethal weapons, area denial, littoral operations*

Background
In recent years, the United States of America and their allies have shifted their military focus from the Middle East and United States Central Command (CENTCOM) area of responsibility (AOR) to focusing in regions dominated by near-peer military adversaries such as China and Russia as defined in the 2017 National Security Strategy. The consistent growth of their economic gains and political influence coupled with unprecedented gains in military capability present unique threats to national security that require dynamic solutions. In order to defeat these threats, the DoD and defense community has been charged to identify methods and ways of increasing lethality and the overall probability of mission success.

Based on the narrowing capability gaps between the DoD and our adversaries, there is a greater need to identify unique systems comprised of currently existing technologies combined with elements that are currently in development to meet those requirements. A potential also exists to reduce casualties associated with near future conflicts in order to reduce potential escalations in an increasingly unstable international security environment. This set of requirements has brought the focus of NLW into the forefront of winning potential future conflicts while being able to de-escalate hostilities to reduce collateral damages. This research project developed a concept to incorporate NLW systems with legacy, lethal weapons systems to provide increased lethality as required by the 2017 National Security Strategy.

Findings and Conclusions

Increasing mission success through increased lethality and/or the provision for diplomatic de-escalatory off-ramps is critical to manage the security focus being placed on the South China Sea (SCS) due to growing Chinese territorial claims and expansion. The militarization of the SCS and illegal sovereign claims present a greater security risk to regional allies from the growing expansion and capabilities of the People's Liberation Army Navy (PLA(N)). These activities could potentially lead to an amphibious operation to advance Chinese security objectives in the SCS.

This research project developed an OLDS to defend against a potential enemy amphibious operation by a near-peer adversary. The study and culminating report identified a potential conflict scenario, order of battle, and subsequent analysis of conflict outcomes between an aggressive PLA(N) amphibious raid against an Armed Forces of the Philippines (AFP) defense of a targeted airfield. The OLDS was developed, modeled, and simulated as both a 'baseline' model comprised of only lethal weapon systems and an 'alternative' model comprised of current NLW and lethal weapon systems. The capabilities that are identified are assumed to be available with a potential deployment of 2025 and seek to deter, disrupt, and potentially deny an enemy amphibious operation. While NLW plays a key role in the implementation of OLDS, other system elements such as logistics support; sensors; command, control, communications, computer, intelligence, surveillance and reconnaissance (C4ISR); etc. must also be considered in the development of the OLDS.

The JP 3-02 *Joint Amphibious Operations* describes the processes and methods for conducting an amphibious demonstration/raid. We referenced the methodology used by the United States Navy (USN) and United States Marine Corps (USMC) to assume that near peer adversaries will conduct amphibious operations in a similar way. The major phases (Plan, Embark, Rehearse, Move, and Act) are the top-level functions of the enemy's amphibious demonstration/raid operations.

Each of these phases is further decomposed to lower level sub-functions and modeled with enhanced functional flow block diagrams (EFFBD). Once the red forces arrive in the operational area, NLW systems ashore will be utilized to disrupt their advance and deter a demonstration/raid operation from being conducted. NLWs utilized ashore would consist mainly of area denial systems and vehicle stoppers. These systems have parameters that are inputs for the model such as power level, range, and effectiveness. These determine the effectiveness of NLWs by modeling and simulating the distance the enemy travels to the objective area, rate of travel, time required to achieve success or to withdraw, and reduction of forces.

Our research team identified a specific order of battle for the OLDS, created architecture models and discrete event simulations, and then conducted statistical analysis between the OLDS baseline (only lethal weapons) and OLDS alternative model (includes lethal and NLW). The research identified that the OLDS alternative model was more effective against a potential enemy amphibious raid resulting in an increased mission effectiveness (defined as the percentage of enemy forces that fail to complete their mission and do not survive through all 5 phases) of 86.33% as compared to the baseline system that proved effective only 42.5% of scenarios. This shows that NLW systems can be integrated to deter, disrupt, and deny enemy amphibious operations potentially reducing friendly force casualties while increasing their lethality and mission success.

Recommendations for Further Research

Further analysis of existing and under-development NLW systems may provide commanders with new and undiscovered capabilities against near-peer adversaries in future projected operating environments. The greatest performance gap is situated in the early detection of the planning phase. NLW systems such as the Saildrones and the Counter-electronics High-powered Advanced Missile Project (CHAMP) could increase the overall effectiveness providing early detection of enemy forces during the planning phase. Additionally, future modeling and simulation should include future NLW developments while working with warfare commanders and the JNLWP to model threats and a system of systems with integration of NLW systems into OLDS to support the defense of the littoral operating environment.

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II Marine Expeditionary Forces (II MEF)

NPS-18-M173-B: Creating a Framework for USMC-Navy Big Data Management by ensuring II MEF framework supports the needs of Marine Expeditionary Force, Expeditionary Strike Group & Navy Aviation Mission Planners

Researcher(s): Dr. Arkady Godin
Student Participation: No students participated in this research project.

Project Summary

The United States Marine Corps (USMC) has a Vision by 2025 to roll out Marine Air Ground Task Force (MAGTF) *Information Environment Operations* (IE Ops) Strategy for the Concept of Employment (COE). The approach taken by the Marine Corps must "adapt to meet the new challenges of a perpetually expanding and increasingly complex *information environment*." The USMC leadership provides further clarification:

> "This approach should be viewed from the maneuver warfare perspective, such that we extend this warfighting philosophy into the information space. … These ideas include operationalizing the information environment as a maneuver space, commanding and controlling information capabilities integrally to achieve objectives, and providing MEF commanders with dedicated organization, tools, and experts to ensure rapidly advancing information capabilities can be planned and executed effectively."

Keywords: *big data, data, information, knowledge, decision support*

Background

The COE identifies the crux of the problem facing the MAGTF: *There is an inadequate mechanism in place for the MAGTF commander to comprehensively understand, plan, and execute IE Ops as an integral component of MAGTF operations.* Today, the MAGTF commander has limited ability to maintain a coherent understanding of relevant threats, vulnerabilities, and opportunities across the information environment (IE); and has limited command and control (C2) mechanisms in place to integrate disparate IE Ops capabilities dynamically across the MAGTF. Additionally, intelligence and other information about many aspects of the IE are, at best, scattered across the MAGTF and external organizations and, at worst, are non-existent. Moreover, there is no organization or C2 mechanism focused on holistically planning and conducting IE Ops. Given the increasing complexity and consequence of the IE, the MAGTF must develop a new approach to maneuvering in the IE and conducting *Information Environment Operations* at the tactical level.

The Vision for MAGTF IE Ops in the 2025 timeframe is to:

> "apply informational power in concert with fires and maneuver to accelerate tempo and achieve physical and cognitive advantage. … In 2025 the MAGTF will be organized, trained, and equipped to sense, understand, and coherently operate within the information environment. Achieving the vision requires developing and integrating four central ideas: (1) planning and executing IE Ops along *functional lines of effort* to enable cohesive and comprehensive planning and employment of IE Ops capabilities, (2) establishing a dedicated MAGTF IE Ops *organization* – the Marine Expeditionary Force (MEF) Information Group (MIG) with an associated Combat Operations Center (MIG COC) focused on integrating IE Ops along the functional lines of effort, (3) building *agile distributed C2 capabilities* to enable collaborative distributed planning and dynamic, decentralized execution, and (4) fusing, analyzing, and using disparate intelligence and other information about the IE through a near-real time *running estimate* that feeds the common operational picture/common tactical picture (COP/CTP), provides planning support, mission coordination, and supports mission assessment."

The II Marine Expeditionary Force (II MEF) sponsor has expressed an interest in how a Big Data Management Architecture can support these four central ideas. The focus of the study was to identify infrastructure-heavy Functional Lines of Effort (FLoE) for the MIG and the MIG COC. The challenge inherent for this study is the inherent "conflict" between the "old running estimate," prescribed in the MAGTF IE Ops CoE Manual (Manual), dated 6 JUL 2017, and the "*new Running Estimate"* that includes a big data management, machine/deep learning and other artificial intelligence (AI) frameworks. The old running estimate is used in the Tactical Service Oriented Architecture (TSOA) to enable integration of the Information Battle Management and Control System's (IBMCS's) agile and distributed C2 capabilities. However, the architecture necessary to build the proposed Data-Information-Knowledge-(DIKU) Knowledge Base (KB) requires a new and different running estimate that will be informed by the Manual. The old running estimate definition presupposed that the DIKU architecture KB would be able to employ the running estimate in an analytical engine within IBMCS, but this is not possible.

Findings and Conclusions

The new *running estimate* cannot be "estimated" from an analytical engine. It will take significantly more effort to dedicate a separate architecture for flexible computations of the *running estimate* for all FLoE, as well as different commands and operational centers. It is anticipated that, as time progresses, even more critical capabilities, currently missing in the mission planning cycle, will emerge.

To summarize, our study proposes that the new *Running Estimate* Architecture (REA) will run side-by-side with the IBMCS TSOA (as opposed to being nested in the IBMCS as an "analytical engine"). This means, of necessity, that some of the IBMCS functions, like IE OPS *Running Estimate* Information Flow, will be migrated from TSOA/IBMCS to the new *REA*. This proposal assumes that the infrastructure-heavy FLoE, #2 Provide IE Battlespace Awareness" and #7 "Control IE Capabilities, Resources, & Activities", rely on the new *running estimate* and IBMCS. Successful integration of TSOA/IBMCS and REA will assure all FLoE, including Functions #2 and #7, enable capabilities of two concurrently running integrated architectures. The REA, which is capable of adapting to events in a dynamic world, will be a superior choice for real-time planning and variations on a published mission order, as compared with TSOA-enabled IBMCS due to TSOA's data sharing rigidity.

Developing a REA and establishing a connection between both REA and IBMCS/TSOA Mission Planning capabilities is fundamental to the "real time" goal toward which the running estimate is driving. Our team believes, for maneuvering, where the information and physical battlespace is significantly affected by the rapidly changing events, the adaptivity in all three dimensions (physical, informational and cognitive) is what matters the most. The key for the physical dimension is to "keep the eyes on the ground" to feed the relevant data. ISR collection planning and C2 assessment feedback loops ensure that is the case. Responsibility of the informational dimension is to extract events and entities which affect the Situation Awareness and Mission Context. Decision-making by the commanders on their missions of responsibility originates from the cognitive dimension. To be called successful, informational dimension should be capable of building the mental model of the battlespace for the commanders at their respective tiers. Our team is confident a prerequisite to the adaptivity lies in the ability of the informational dimension to extract all dynamic events from all incoming data sources. We should never ignore information on the entities as they are the facts for the entity properties of the raw maneuvering event graph. This graph establishes a baseline for the course of action (COA) selection process under dynamically-changing battlespace conditions. For a graph to be actionable, it must be containing a meaning requiring integration with events based on dynamically-generated ontologies. The Informational dimension must also perform a reduction of a graph to ensure commander's comprehension. Aggregation over event ontology hierarchies, where the highest levels of ontology would be expressed in "commander-level ontology" on how they think of actionable events, will result in feeding reduced and valuable information into the cognitive dimension to ensure quick and high-quality decisions on how to maneuver the forces under complex battlespace situations.

Recommendations for Further Research

Current focus of the continuation of the study will be concentrated on initial proof-of-concept based on experimenting with the transformation of the spatially-oriented maneuvering entities data (objects and subjects) into the temporally-oriented maneuvering events data (directionality and speed). This approach has no restrictions for any data modality. We will start experimentation with the "structured activity data" by infusing meaning to this data. However, our team views "natural text" as capable of expressing entities and, most importantly, events, to generate a "raw maneuvering event graph". "Event" path of research is consistent with Situational Awareness (SA) model developed by Dr. Mica Endsley, world-class expert in SA. Her SA model's highest level of cognition (Level 3) is able to project future states and events.

Marine Corps College of Distance Education & Training (CDET)

NPS-18-M021-A: Deep Analytics for Content Management System (CMS)

Researcher(s): Dr. Ying Zhao
Student Participation: Capt Anthony Rybicki USMC

Project Summary

The researchers investigated the needs of the College of Distance Education and Training (CDET) Content Management System (CMS) and identified the significant capabilities and measures of effectiveness (MoEs) these systems utilized. Our research examined which capabilities and MoEs may enhance the training and education platform/environment offered within the Marine Corps

Distance Learning Network (MarineNet) learning ecosystem. The research identified which data should be captured and which metrics should be analyzed. Since actual CMS data was not available, other proxy data sources were identified such as KDD Cup data, NIH UK, and NPS thesis data. Once we can access as the CMS pilot data, we identified various big data and deep learning tools such as Tableau, D3, Python SciPy, NetworkX, RapidMiner, R, Octave, WeKa, and Google Analytics that would be useful in analyzing the data. CDET will use this information to determine and define appropriate electronic learning (or distance/distributed learning) MoEs.

We addressed the following five research questions:

- What constitutes MoEs for training and education distance learning materials in an enterprise level collaboration-learning environment?
- Within the Adobe Enterprise Manager (AEM) CMS, what data needs to be collected, and how can this data support the identified MoEs?
- How can the CMS determine the effectiveness of MarineNet's training and education platform?
- What analytic attributes, inherent within AEM and/or Adobe Analytics, are essential for CDET to collect, analyze, and present useful information in a real-time, intuitive, adjustable, and visual manner (dashboard) to support the identified MoEs?
- How can the CMS support a dashboard that allows for data manipulation, aggregation, and visualization of identified MoEs?

Keywords: *big data, deep analytics, visual reports, personalized learning, massive open online courses, measures of effectiveness, learning management, distance education and training*

Background

We see the potential for the MarineNet platform to deliver personalized learning including micro-learning--targeted learning either for certain groups, a specific student, or perhaps identified learning styles of the student [ref 7]. The technology can support personalized learning through Experience API (xAPI)— an e-learning software specification that allows learning content and learning systems to speak to each other in a manner that records and tracks all types of learning experiences. Learning experiences are recorded in a Learning Record Store (LRS). The LRS allows the sharing of data driving many types of learning analytics, both existing and new ones to be identified in the future. However, the technology isn't the full solution because content must support learning outcomes/objectives and learning must be assessed to measure and improve the learning process. This is accomplished by selecting valid measures of effectiveness. To answer the five research questions, we studied current learning theories and, using existing and available MarineNet data, selected MoEs to support those constructs to assess if learning took place. The MoEs and the selected subset of MoEs were based on accepted pedagogical theory and practice as well as on our exploration and evaluation of various learning models that may measure learning or training or at least measure some of their correlations. Specific MoEs are needed in order to select meaningful data for the learning/training metrics but must be based on the state-of-the-art current understanding of learning and the acquisition of knowledge.

Initial research identified 36 MoEs from the Student Profile and Content Profile data categories that could be supported by the pilot data and perhaps even by Adobe Workbench. The two data sources that were identified as meaningful sources for the MoEs are:

- Student Profiles
    - Bio/demographic form for each student. The data may not be very rich.
    - Student learning result data: Pre/post and intermediate tests tagged for learning objectives so we can have counts/percentages at various aggregation levels. Measures for learning are often unique to disciplinary fields or individual cohorts or communities. What will we see more/less of because of training and education in the form of measures such as grades?

    - Student learning behavior data: Concept measured by the Learning Behavior Scale (ref. 1) that includes items such as: attention to tasks, positive attitudes about academics and school, competence, motivation, problem-solving skills, and flexibility in information processing. Canivez has suggested that LBS is generally based on classroom observation, but it is possible to some extent, to be done by online analysis of generated data (ref. 2). The student profiles may be partially derived from the clickstream data of the online learning websites.
- Content Alignment Profiles
    - Courseware includes: lecture videos, forums, blogs, online/offline research, and references and their clickstream data. This will be the core data from pilot.
    - Content alignment data: The MoEs in this category assumes (not always the case in practice) the alignment of course outcomes and objectives with suitable learning experiences, appropriate assessments that measure progress toward course outcomes, and grading practices that reflect the degree to which students actually achieve course outcomes.
    - More cognitive level of analysis: For example, how to measure critical thinking? Can knowledge categorization data and measures of learning help to articulate holistic answers for important questions—with attributes that are context and content dependent?

The MoEs and the selected subset of MoEs were based on accepted pedagogical theory and practice as well as on our exploration and evaluation of various learning models that may measure learning or training or at least measure some of their correlations. These MoEs are required to select meaningful data for the learning/training metrics but should be based on the state-of-the-art current understanding of learning and the acquisition of knowledge.

The following were initial starting points from theory to best practice:
- Bloom's Taxonomy (ref. 3, 4) is a classic model of learning. Bloom's model classifies learning into factual, conceptual, procedural, and metacognitive and the subsequent cognitive dimensions required. Bloom's Taxonomy shows a multi-dimensional learning process and by implication requiring various measures of these multi-dimensional attributes.
- Kirkpatrick Model (ref. 5) focuses on the degree the learner interacts with the content in each of the four levels:
    - Reaction: degree to which training is favorable, engaging and relevant to their jobs.
    - Learning: degree to which participants acquire intended knowledge, skills, attitude, confidence, and commitment based on their participation in the training.
    - Behavior: degree to which participants apply what they learned during training.
    - Results: degree to which targeted outcomes occur as a result of the training.

Findings and Conclusions

The research identified which data should be captured and which metrics should be analyzed. Since actual CMS data was not available, we used other proxy data sources such as KDD Cup data, NIH UK, and NPS thesis data. Two meaningful data sources were identified for our selected MoEs, Student Profiles and Content Alignment Profiles.

To answer the five research questions listed earlier, we studied current learning theories and, using existing and available MarineNet data, selected MoEs to support those constructs to assess if learning took place. The MoEs and the selected subset of MoEs were based on accepted pedagogical theory and practice as well as on our exploration and evaluation of various learning models that may measure learning or training or at least measure some of their correlations. Specific MoEs based on the state-of-the-art current understanding of learning and the acquisition of knowledge were selected from a list of candidates that could be potentially mapped to meaningful data for the learning/training metrics.

We summarize our findings for our five research questions:

Question 1: Within the Adobe Enterprise Manager CMS, what data needs to be collected, and how can this data support the identified MoEs?
Despite the inherent limitations of any learning measure, we've identified what we believe constitutes appropriate measures of effectiveness (MoE) based on current learning theory and practicality since they need to be mapped to sources of learning data including content alignment, student, student learning, student learning behavior, and content knowledge categorization.

Question 2: Within the Adobe Enterprise Manager CMS, what data needs to be collected and how can this data support the identified MoEs?

We reviewed the MarineNet pilot project requirement document, for example, and identified MoEs that the data requirement supported. Just one example; Course development->student preview mode (2): The data can be used to build reports to show how long the students stay in the preview page and how the length of stay correlated to the Reaction Engagement MoE[5], Results MoE[8], Learning MoE[6], Behavior MoE[7], and Cognitive MoEs[9-14].

Question 3: How can the CMS determine the effectiveness of MarineNet's training and education platform?

We studied measures of effectiveness for CDET based on the learning theories and best practice (answers for Question 1). We also studied possible big data collection based the capability requirement document that can be implemented using the CMS in AEM (Answers for question 2). The overall effectiveness of MarineNet's training and platform can be then determined after running the MoEs through the big data using the analytics. This must be validated by future work on real data such as the MarineNet pilot project.

Analytic requirements include business intelligence, data mining, machine learning, and predictive analytics tools related to the preceding categories of analytics. The analytic types include user profiling, cohort analysis and predictive analysis.

Question 4: What analytic attributes, inherent within AEM and/or Adobe Analytics, are essential for CDET to collect, analyze, and present useful information in a real-time, intuitive, adjustable, and visual manner (dashboard) to support the identified MoEs?

There are many machine learning algorithms (user segmentation and prediction). We have used Weka, a free tool including many famous algorithms. We also identified various big data and analytics tools such as Tableau, D3, Python SciPy, NetworkX, RapidMiner, R, Octave, WeKa, and Google Analytics. JMP and Orange for machine learning (https://orange.biolab.si/) are tested as well. JMP and Orange are standalone tools and have no issues for uploading sensitive data to a cloud, can be alternatives to tableau and WeKa for machine learning.

Question 5: How can the CMS support a dashboard that allows for data manipulation, aggregation, and visualization of identified MoE?

We examined a couple of open source tools and data in this area as listed examples of visualizations for the future pilot data as the answers for this question. We found several tools very useful to support the CMS including Tableau and Orange, and we identified MoEs and supporting data that could be used to assess the transfer of knowledge on the MarineNet platform to students. We provided examples of the types of analytics that are useful for AEM, Adobe Analytics, and Workbench to implement these MoEs.

We identified MoEs and supporting data that could be used to assess the transfer of knowledge on the MarineNet platform to students. We provided examples of the types of analytics that are useful for AEM, Adobe Analytics, and Workbench to implement these MoEs. These tools are examples for how data can be manipulated and displayed visually.

Recommendations for Further Research

Future work has been approved as described in NPS-19-M159, Deep Analytics for MarineNet with Personalized Learning (Continuation*).* The focus will be on the two of the five learning data sources: "content alignment" and "student profiles", and the supporting MoEs as discussed in this report. The main source is content clickstream data in the pilot project collected and will be from web pages and links which then tie to each content and student. MoEs that we will focus on the MOEs that would give us a higher probability of producing meaningful results given the scope of the follow-on project.

A sample list of just a few of attributes we will investigate next year:

- content in a courseware:
  - Number of enrollments
  - Number of completions
  - Number of views
- contents in communities
  - Top number of viewed content items
  - Top number of downloaded content items
  - Top number of favored content items
- collected for community details
  - Top number of content items viewed
  - Bottom number of content items and time elements viewed
  - Mandatory time element (daily, weekly, or monthly)
- The synopsis of comments. The data can be also used to link the student profiles as follows:
  - Number of visits
  - Total number of views for content
  - Number of subscribers

The MoEs for FY19 will mostly use the clickstream data, but if there are other opportunities we will explore them. What is essential is that we get real live data from the ongoing MarineNet pilot projects. MarineNet pilot data will allow us to focus on targeted MoEs supported by real data that would give us a higher probability of producing meaningful results for MarineNet decision making.

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Marine Corps Modeling & Simulation Management Office (MCMSMO)

NPS-18-M145-A: Assessing the Effect of RAMS on Marksmanship-Troubled Recruits for Initial Rifle Qualification

Researcher(s): Dr. Meghan Q. Kennedy, Mr. Perry McDowell, Ms. Rabia Khan, and Mr. David Reeves
Student Participation: No students participated in this research project.

Project Summary
The Modular Advanced Technology-Marksmanship Proficiency Toolkit (MAT-MP) is a newly developed prototype to address the need for a Rapid Assessment Marksmanship System. The Marine Corps Training and Education Command (TECOM) tasked the Naval Postgraduate School (NPS) with evaluating the effectiveness of the MAT-MP as a marksmanship-coaching tool. Specifically, TECOM wants to know if use of the MAT-MP (1) reduces the number of qualification attempts needed to pass and (2) improves qualification scores of troubled shooters (those who fail the first qualification).
This evaluation was a joint effort between Weapons and Field Training Battalion, Parris Island (WFTBn-PI) and NPS. With input from WFTBn-PI, NPS designed the evaluation and specified the data collection procedures. NPS also provided training on data collection, transmission, and storage; conducted data analysis and provided this final report. WFTBn-PI provided trained personnel to collect and handle the data. The NPS and Marine Corps IRB determined this evaluation did not meet the criteria for human subject’s research.

The evaluation is based on data from 67 qualification attempts: 32 attempts from 25 troubled recruits who received regular coaching during the 2nd and greater qualification attempts (control group) and 35 attempts from 22 troubled recruits whose coaches used the MAT-MP during the 2nd and greater qualification attempts (MAT-MP group). Results indicated that the MAT-MP group showed significantly greater improvement in overall qualification scores from initial attempt to final attempt than the control group, but required more attempts to pass. These results may be due to the MAT-MP group being more troubled (i.e., having significantly poorer initial qualification scores) than the control group. Results are not explainable by differences in coaching experience between the MAT-MP coaches and the control coaches.

Keywords: *marksmanship, weapons training, MAT-MP, training effectiveness, initial qualification*

Background
It is essential that each Marine have superb combat marksmanship skills. Recruits receive two weeks of combat marksmanship training, at the end of which, they attempt to pass a qualification (initial qualification). This training is highly demanding in terms of human and equipment resources. Although large majorities of recruits pass the initial qualification, the remaining must redo the qualifications with a different company until they finally pass. Thus, increasing the pass rate on the initial qualification would lead to reductions in ammunition usage, remedial training, and attrition. Because accurate marksmanship skills relies on a complex interaction of perceptual-

motor, cognitive and affective factors, several methods for improving marksmanship instruction have been tried (Bewley et al, 2003; Chung, et al, 2011). These methods include adding video-based introduction to marksmanship (Chung et al, 2009), use of neurophysiological measures to capture the psychophysiological characteristics of experts (Behneman, et al, 2012) and applying sensors to the rifle to detect factors such as breath control (Espinosa et al, 2008). While these methods have shown some success, they do not adequately reduce instructor and training costs. The Modular Advanced Technology-Marksmanship Proficiency Toolkit (MAT-MP) is a newly developed computer based tool for marksmanship assessment in which data from sensors and a camera attached to the weapon are automatically calculated into relevant performance metrics and wirelessly transported to a tablet operated by the instructor. Thus, it should enable an instructor to identify issues based on a single shot rather than multiple iterations, as is currently required. If successful, MAT-MP has the potential to simultaneously improve first qualification pass rates and reduce costs.

Findings and Conclusions

To determine the training effectiveness of MAT-MP, we conducted a pilot study to explore whether if use of the MAT-MP (1) reduces the number of qualification attempts needed to pass and (2) improves qualification scores of troubled shooters (those who fail the first qualification). Thus, this study directly relates to the Weapons and Field Training Battalion mission of providing the most effective instruction in rifle marksmanship to recruits to meet the greater goal of producing the highest quality Marines.

<u>Data collection approach</u>: We used a blocked design with a sample size of 47 troubled recruits on whom qualification data from re-attempts were collected. Each week, troubled recruits were ranked in terms of severity of their marksmanship difficulties as indicated by their first qualification score. The worst eight were blocked into the MAT-MP and control group such that of the worst two recruits, one was assigned to the MAT-MP group; the other to the control group. This process was repeated for the remaining six recruits. We also attempted to ensure that there were equal numbers of female troubled recruits in each group. This design was chosen because it should control for variability between recruits, as well as any environmental factors that may occur on a given week. We also aimed to control for variability in instructors' level of instructing experience.

<u>Statistical methods:</u> Two sample *t*-tests assuming unequal variances or the Wilcoxon rank sum test were used to address the main research questions. Two factor ANOVA with LSD multiple comparisons were used for to examine any potential gender by group interaction effect on the number of qualification attempts and improvement from initial qualification score to final qualification score. Criterion for rejecting the null hypothesis (H0) was set at one-tailed alpha levels of .05. Data analysis was conducted under the guidance of a statistician who specializes in small sample sizes. Descriptive statistics were computed regarding MAT-MP usability in terms of amount of set-up time and frequency and type of issues that occurred with the MAT-MP during data collection.

<u>Results:</u> On average, the MAT-MP group had significantly more attempts than the control group (Mean MAT-MP attempts: 2.68 (SD = .72); Mean control attempts: 2.28 (SD = .54), $t(38.85) = 2.15$, $p = .02$. This difference may be due to the MAT-MP group having worse initial qualification scores than the control group (Mean MAT-PM score: 148.95 (SD = 23.19), Mean Control score: 160.91 (SD = 18.01), $t(37.70)=1.90$, $p = .03$.

On average, the MAT-MP group improved significantly more from the 1st attempt to the final attempt in qualification score than the control group (Mean MAT-MP improvement:40.52 (SD = 23.32); Mean control improvement: 23.38 (SD = 25.73), $t(39.62) = 2.26$, $p = .02$. This result is not due to any differences in coaching experience between the MAT-MP and Control coaches: There were no significant differences between Control and MAT-MP coaches in terms of time coaching (Wilcoxon test: $z = .19$, $p = .82$) or the number of details (Wilcoxon: $z = .43$, $p = .67$).

MAT-MP installation onto the rifle and getting connectivity took on average 75.71 min (95% CI: 57.88 – 93.55). Although it only took a few minutes to install MAT-MP onto the rifle, achieving connectivity with the tablet consumed the remaining minutes. Of the 35 times the MAT-MP was used, there were 16-recorded instances of issues. Typical issues were lost/ intermittent connectivity, RCO hitting the recruit's head; trigger sensor problems, battery dying.

Recommendations for Further Research

This evaluation focused on the effectiveness of a single marksmanship training aid system, the MAT-MP. One recommendation for future research is to determine the feasibility and utility of developing a toolbox of combat marksmanship instructor (CMI) training aids. This toolbox could consist of existing and prototype technologies: some tools would be used during grass week to improve all recruits' marksmanship skills; others would be used to identify troubled recruits; still others would be used during live fire to verify instructors' hunches as to why a troubled recruit was having difficulty. By having multiple CMI training aids at their disposal, the WFTBn-PI could aid their mission of providing the most effective instruction in rifle marksmanship to recruits.

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NPS-18-M034-B: Automated Data Analysis for Network Optimization and Threat Detection in Network Architectures

Researcher(s): Dr. Frank Kragh, Mr. Arijit Das, and Ms. Donna Miller
Student Participation: Capt Ben Brida USMC

Project Summary

The Marine Corps Network Efficiency Lab (MCNEL) is tasked with analyzing very large network traffic archives collected from operations in order to improve future network design, operations, and security. Until this time, MCNEL has used conventional single node packet analyzers, which have proven to be very limiting. Conventional single node packet analyzers are unable to monitor network traffic at scale. In this research, elements of the Apache Hadoop ecosystem, including HBase, Spark, and MapReduce were employed to conduct network traffic analysis on a large collection of network traffic thereby establishing a prototype for network analysis at very large scale in computer clusters. The MCNEL clusters could be organic or in the cloud, perhaps using govCloud cloud computing assets. Initially, limited analysis was conducted directly on packet capture next generation (pcapng) files on the Hadoop Distributed File System (HDFS) using MapReduce. To allow for repeated analysis on the same dataset without reading all source files in their entirety for every calculation, network traffic archives were parsed, and relevant meta-data was bulk loaded into HBase, a Not Only Structured Query Language (NoSQL) database employing the HDFS for parallelization on computer clusters. This NoSQL database was then accessed via Apache Spark where pertinent data is loaded into dataframes, and additional analysis on the network traffic takes place. This research demonstrates the viability of custom, modular, automated analytics, employing open-source software to enable parallelization, to conduct traffic analysis at scale.

Keywords: big data, Hadoop, Spark, MapReduce, HBase, packet capture, pcapng, network analysis

Background

In the analysis of large volumes of data, parallelization is a key tenet that solves several problems. The first problem addressed is read/write access limitations. While disk storage capacity has increased one hundred-fold in the past two decades, read speeds on most drives have only increased by a factor of twenty-five [White2015]. Rather than storing all data on a single drive, we can instead partition and store data on hundreds of drives with shared access. By allowing for simultaneous reading of data on multiple drives, parallelization allows for tasks to be completed in a fraction of the time. Second, parallelization not only increases our data reading speed, it also increases our data reliability through redundancy. For example, by storing partitioned data in triplicate on physically separated hard drives, the likelihood of data loss is reduced dramatically. Finally, we can greatly increase our processing power through parallelization. By storing data on two, two hundred, or two thousand servers and allowing each server to individually do the processing of the data it stores, we not only reduce the required network traffic to move and manage data, but we also vastly increase our effective processing power [White2015].

For MCNEL's purposes, it was assessed that using open source software on commodity hardware is most likely to be maximally scalable and financially supportable. Because of those considerations, the Hadoop ecosystem was selected as the large-data framework to be used. For increased functionality and ease of implementation, for this thesis specifically, MapR was employed. MapR is a third-party Hadoop distribution; however, any properly configured Hadoop cluster would be equally viable. Finally, packet capture next generation (pcapng) was selected as the expected file type for analysis, since network collections conducted by MCNEL use this format.

Findings and Conclusions

The purpose of this research was to provide the Marine Corps Network Efficiency Lab with a prototype capability to conduct automated, large scale packet analysis. This was done employing open-source software designed for use on commodity hardware, specifically, the Apache Hadoop ecosystem. This research took an incremental approach, first seeking to conduct network analytics on Packet Capture Next Generation (pcapng) files using MapReduce. After a successful evaluation on the strengths and limitations of MapReduce for analysis, a more structured storage mechanism than pcapng was sought.

HBase, an open source NoSQL database employing the HDFS, was selected as a preferred storage mechanism, where columns could be dynamically assigned based on packet protocol, and packet data could be separated from metadata. This separation allows for access to data without sequentially reading every file in its entirety. HBase data was then mapped to a Spark DataFrame to conduct multiple types of analysis and more sophisticated analysis than is practical in just MapReduce.

The types of analysis conducted were traditional network metrics, most of which are already performed by the Marine Corps Network Efficiency Lab. The emphasis was on evaluating these metrics in a big data framework, allowing for scaling to many nodes simultaneously and completing the work on terabyte and petabyte size data sets. While only a single node virtual machine was used for this research, input data sizes larger than allocated memory were used to validate the concept of scaling, and the code produced is viable for use on an arbitrarily large Hadoop cluster.

The metrics calculated in MapReduce were network usage per Internet Protocol (IP) address, port counts, protocol counts, and network usage by hour of day and day of week per IP address. The network usage by IP address and port count metrics were repeated in Spark. Additionally, IP protocol count and Transmission Control Protocol (TCP) initial round trip time metrics were also calculated in Spark. Even operating in a single node virtual machine, the code executed in this research was able to often outperform a free-ware packet analyzer in terms of speed. In some cases, substantial performance increases were obtained.

Ultimately this research demonstrated the viability of the Apache Hadoop ecosystem for automated bulk data analytics on pcapng network traffic archives, with all prototype software written for execution on a large computer cluster, thereby enabling automated data analysis of very large data sets. In doing so, the whole file input format class and record reader class from [White2015] were used with a custom class developed to directly ingest pcapng files into Hadoop without requiring an intermediary file format. This capability was coupled with custom analytics, developed to determine network metrics in both MapReduce and Spark, using HBase as a long-term storage format.

Recommendations for Further Research

There are four goals which may be pursued as future work on this project.

1. Increasing Functionality and Supported Protocols

The first goal is to increase the capability of the pcapng class used for parsing the files. At a minimum, IPv6 supportability should be added. As IPv6 continues to expand this becomes increasingly relevant. Once this support is added to the pcapng parsing methods, the analytic code will have to be revised to check for protocols and extract metadata as needed, similar to what was done in this thesis by confirming IPv4 and TCP in the HBase bulk loading.

2. Verify capacity with Large Cluster and Large Collect

The second goal is to verify the capability explored in this thesis with a large dataset, either on a local Hadoop cluster or employing a cloud service such as Amazon Web Services (AWS). An additional requirement that accompanies this future work is to obtain a large scale persistent collect from a network. Ideally several weeks or month of data should be gathered, and terabytes of network traffic should be analyzed.

3. Employ Machine Learning to Establish Baselines and Automatically Identify Anomalous Network Behavior

The framework and software provided in this research provide a platform for advanced analysis of huge network traffic data sets including automatically identifying normal and abnormal network traffic. This should be exploited by employing standard machine learning algorithms to analyze the data set for anomaly detection. For example, the provided framework allows easy determination of the average network usage of every IP address, organized by time of day and day of week. This, and similar data, can be used to determine if that IP address is acting abnormally. Similar questions can be asked for latency, given that we can easily determine the initial round trip time (iRTT) distribution from each IP to IP connection. Support vector machines, Gaussian mixture models, or clustering algorithms are standard machine learning algorithms that could be applied to classify abnormal latency. This research effectively established the data framework for the data preparation necessary to answer these questions. A large traffic collection is needed for this work. Months of data would be needed for evaluation and ingestion to have reliable output. Accordingly, once the second goal of verifying capacity with large collect is satisfied, machine learning for network anomaly detection should be explored.

4. Increase Ease of Analyst Use and Improve Metric Output Formatting

The final goal for future work would be to create a user interface for an analyst to easily run the underlying algorithms. By having an interface where queries can be easily submitted, specifically controlling what data is ingested into Spark from HBase, what metrics are calculated, and how they are presented, the utility of this thesis capability development would be drastically increased. Additionally, currently metrics are produced exclusively in table format. By exploring a dashboard, graphical outputs could be easily included and automatically generated, increasing the utility and interpretability of the analytics being conducted.

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Marine Forces, Pacific (MARFORPAC)

NPS-18-M091-A: Bulk Fuel Delivery in Support of Expeditionary Advance Base Operations

Researcher(s): Dr. Alan Howard, Brandon Naylor, Mr. Lawrence Walzer, and Mr. Jack Templeton
Student Participation: Mr. Cody Reese CIV

Project Summary

This research sought to explore ship-to-shore bulk fuel delivery solutions for Marine Corps distributed forward expeditionary base operations in littoral regions with heavy Anti Access/Area Denial (A2AD) considerations. The primary focus areas of this study consisted of creating a systems engineering approach to evaluate an amphibious fuel delivery system's ability to meet bulk fuel needs, and a computer model to evaluate how such a system would interact with the combat logistics fleet and supporting naval units. The researchers were unable to find reliable estimates for

campaign-level fuel needs for distributed amphibious operations, and current doctrine on amphibious fuel distribution predates current operating paradigms and emerging A2AD threats by near peer adversaries. To address this lack of data on estimated fuel demand and growing threats to logistical assurance, secondary efforts in this study sought to explore bulk fuel needs through base resiliency studies and a wargame intended to explore how operational planners ashore respond to anticipated disruptions in amphibious fuel deliveries. These secondary efforts were intended to establish a minimum acceptable distribution capacity.

The research team is unable to propose formal specifications for an amphibious bulk fuel delivery system at this time, but the products of this study should help inform future efforts to evaluate the suitability of proposed amphibious bulk fuel solutions. The systems engineering analysis of the amphibious fuel transfer problem should help inform the future design or fielding of fuel transfer mechanisms, while the improved logistics model can provide insights into the Navy's ability to support such a system.

Keywords: *logistics, energy, fuel, supply, bulk fuels, ship-to-shore, littoral, South China Sea, A2AD*

Background

Recent tensions in the South China Sea have spurred the need to prepare for future conflict in distributed littoral regions with heavy A2AD considerations. The Marine Corps has proposed a distributed forward expeditionary base concept to conduct operations in such environments, but this operations model relies on ship-to-shore bulk fuel delivery to meet the fuel needs of troops on the ground. Current Navy and Marine assets are not up to the task of delivering bulk fuels in contested littoral environments without pier or port infrastructure to facilitate liquid supply transfer.

The most recent Marine Corps doctrine specifying requirements for amphibious fuel delivery assets was drafted in 1984 when fuel demand was much lower and potential adversaries did not possess the capabilities to reliably target fuel transfer assets from shore. Current amphibious fuel delivery methods rely primarily on either amphibious landing craft deployed from a large deck amphibious assault ship class such as the LHD, or a long hose deployed from a specialized tanker. Both of these delivery methods lack the bandwidth to support ground operations in a large scale conflict, and both methods require positioning a high-value asset within striking range of a near-peer adversary's A2AD capabilities.

Findings and Conclusions

This study had originally proposed to evaluate different configurations of existing amphibious fuel delivery assets or propose requirements for novel amphibious fuel transport designs that could effectively meet the Marine Corps' amphibious bulk fuel distribution needs, but a change of scope was deemed appropriate mid-project. After conducting our literature review, it became clear that previous research efforts have established a consensus that currently fielded assets are not up to the task, and other research teams with more operational experience and better access to relevant data are already working to propose new systems. Instead of attempting to propose an uninformed solution, this effort has instead focused on creating a framework to determine the capability and suitability of solutions proposed by other groups.

The two main foci for our study consisted of a student-led effort to determine the key requirements and measures of effectiveness for a proposed amphibious bulk fuel transfer system, and developing a naval operations model that could be used to evaluate the Navy's ability to support such a system. The system requirements definition effort used the results of prior studies, doctrine, and wargames to conduct a robust systems engineering analysis on the qualifications that must be met for a bulk fuels system to meet stakeholder needs. The modeling analysis effort consisted of improving an existing surface fleet fuel analysis model, Fuel Usage Study Extended Demonstration (FUSED), and to incorporate missions where Combat Logistics Fleet ships would deploy ambiguous fuel delivery systems with user-defined specifications, and track how fulfillment of the amphibious bulk fuel transfer mission impacted other naval operations. Secondary efforts to understand expected fuel consumption ashore were to be used as the amphibious fuel demand signal within the FUSED model.

Although the research team does not recommend a specific platform for bulk fuel transfer at this time, our results should help inform the design or fielding of other fuel transfer solutions. The thesis entitled "*Development of System-Level Requirements and Effectiveness Measures for an Amphibious Fuel Distribution System*," by Naval Postgraduate School student Cody Reese describes the necessary design requirements for a system to meet the Navy and Marine's bulk fuel transfer mission as currently defined. The FUSED model has been tested with mission parameters and platform design specifications that offer insight into system supportability.

Recommendations for Further Research

Bulk fuel delivery is a long term problem that will continue to evolve as adversaries advance their A2AD capabilities, but the modeling capabilities and system requirements definitions created through this study can help inform future solutions. The research team recommends the products of this research be used to inform future and ongoing efforts to develop solutions to the amphibious bulk fuel transfer problem.

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NPS-18-M261-A: Coastal Marine Spatial Planning

Researcher(s): Dr. Arlene Guest, and Dr. Tom Murphree
Student Participation: No students participated in this research project.

Project Summary

The primary goal of this project was to develop data sets and tools to facilitate coastal marine spatial planning (CMSP) for the U.S. Pacific islands. We have identified and collected over 200 datasets into a comprehensive data portal organized into the sub-regions of American Samoa, Guam, Commonwealth of the Mariana Islands, and Hawaii, and further organized by data categories. We have also developed several types of geographic information systems (GIS) mapping applications in order to help government agencies, stakeholders, and the general public visualize and use the data. We have also documented and organized the datasets in order to facilitate a smooth transition to a final hosting and managing site. We have coordinated and collaborated with the Pacific Islands Regional Planning Body to help in their efforts in CMSP.

Keywords: *coastal marine spatial planning, CMSP, Pacific Islands, Guam, American Samoa, Hawaii, Commonwealth of the Northern Mariana Islands, GIS, data portals, ocean, marine planning, coastal management, environmental conditions, climate, infrastructure, benthic habitat, mapping, geographic information systems, geospatial, decision support, Executive Order 13547, energy, installations, environment, training, testing, natural resources, encroachment, U.S. Marine Corps Pacific, U.S. Pacific Fleet, U.S. Pacific Command.*

Background

In 2010, Executive Order (E.O.) 13547 *Stewardship of the Ocean, Our Coasts, and the Great Lakes*, established the National Ocean Council (NOC) and among other things, directed "the development of coastal and marine spatial plans that build upon and improve existing Federal, State, tribal, local, and regional decision-making and planning processes." The Pacific Islands Regional Planning Body (PIRPB) was established in 2013 to guide those planning processes for the region encompassing American Samoa, Commonwealth of the Mariana Islands (CNMI), Guam, and Hawaii; its members consisted of representatives from eight federal and nine non-federal agencies.

Coastal marine spatial planning is a major component of the national ocean policy and involves: (1) collecting and analyzing coastal marine data; (2) identifying ocean uses and activities; (3) assessing potential areas of use compatibility and incompatibility; (4) collaborating with scientists and other experts; and (5) engaging stakeholders. The benefits to DoD include improvements in: (a) siting and scheduling of training and testing; (b) natural resource permitting; and (c) addressing encroachment on bases and training areas. The main goal of this project was to develop data sets and tools to facilitate coastal marine spatial planning. This includes, for example, collecting data and developing data sets and creating analysis and decision support tools. These datasets and tools serve to help develop a more comprehensive understanding of what the current ocean uses are and identify potential areas of compatible and incompatible ocean uses.

In June 2018, President Trump issued an executive order that revoked E.O 13547, and disbanded the regional planning boards. This disrupted the coordinated planning process that was taking place, but the new E.O. encourages information- and science-based planning, so we expect that our project results will be valuable as the sub-regions continue to develop their coastal plans.

Findings and Conclusions

Data collection was a major component of this project. The territory of American Samoa was chosen to be the first to work on its ocean plan as a sub-region, and so we concentrated much of our effort on collecting data for that territory. We collected or created a total of 75 datasets for American Samoa. We collaborated with a subcommittee of the PIRPB, named the "Data Team" who were experts in data sets or GIS issues from the region. Input was solicited from stakeholders in American Samoa, and feedback was given to us on what data layers they needed. In conjunction with the Data Team and after researching what other regional planning bodies were doing, we organized the datasets into categories:

- Physical Geography: bathymetry, topography, soils, geology, hydrology and coastlines.
- Administrative: counties and villages, population, boundaries such as the coastal zone and National Marine Sanctuary boundaries, harbor facilities, ship transit lanes and ship traffic data, submarine cables, aids to navigation, and transportation infrastructure.
- Marine Species of Interest: marine mammals, birds, reptiles and amphibians, fish, invertebrates, corals and ocean vegetation and benthic habitats.
- Ocean and Atmosphere Characteristics: This includes both real-time observations and forecasts for environmental conditions such as waves, temperature, winds, precipitation, sea level, and precipitation.
- Water Quality: wastewater sites
- Use and Activities: This is further subdivided into eight different categories of fishing, ten recreational activities, six commercial uses, cultural and historical sites, and research and educational activities.
- Climate Change: vulnerable coastlines, flood hazard zones

The data categories for the other sub-regions vary slightly. For example, military uses are included only for sub-regions that have them. (American Samoa does not but the other sub-regions do.)

Some of the datasets were created by extracting data for the sub-region from larger datasets. For example, the National Register of Historic Places has data for all of the U.S., so we extracted records for each sub-region from it. In other cases, we created GIS layers from textual or graphical information. For example, we used engineering blueprints and annotations to add information on newly installed submarine telecommunications cables between Hawaii and American Samoa. In other cases, we located web services for the datasets and have the portal point to those locations. This is ideal for real-time data and forecasts, since the data is automatically updated.

The data portal resides at http://www.oc.nps.edu/CMSP. The utility of the data portal is that all stakeholders and potential users have access to the same data to work from, and do not need to seek out the best and most current data themselves. They can easily see what layers are available for a particular location, and all the information about those layers. All data is in the public domain, and none of it has any restrictions on its use. The portal contains separate sites for each of the sub-regions. For each dataset, we created a screenshot of the data so that users could see a sample of the data and the spatial coverage. Each dataset has a link to download it and/or a link to the web service or interactive map. Each data set also has a link to metadata or information about the dataset. Creating metadata for the layers that did not already have metadata—including datasets that we created ourselves and many of the datasets obtained from agencies—was a time-consuming but necessary effort. All the datasets are required to have metadata in order to be included in the portal; without the metadata, potential users cannot determine whether or not it suits their particular purpose and details such as the date the data was collected and any quality control measures or processing that was done on the data. We also created spreadsheets of the datasets with information and a guide to the datasets briefly describing the datasets for users. We also created a search utility on the website so that users can search by keyword.

Another aspect of this project was to create decision support tools to aid in marine spatial planning. We accomplished this through the implementation of web-based interactive mapping applications. We created some with limited specific capabilities and some with more data layers and open-ended visualization and data exploration capabilities. For instance, one map app allows any user with a browser to draw a track line by clicking points on the map, and the app will provide a topographic elevation profile of that transect.

Another product that we created was a story map for activities and uses in and around Pago Pago Harbor in American Samoa. The interactive story map describes each use and shows where that activity or use occurs in the harbor. It contains about 30 layers of fishing, recreation, and commercial uses, many of which overlap.

We also created interactive maps such as thematic maps showing one type of data, for instance various species distributions in American Samoa. We also created a comprehensive map app that includes all relevant layers, and allows the user to zoom and pan in the map, and click layers on and off. Users can also upload their own data layers or draw points or areas on the maps, add their own titles and text annotations to the maps, and save or print them. These interactive applications provide powerful tools to allow users to do preliminary planning, see what uses and activities already exist in a location, and avoid potential use conflicts.

Finally, as part of this project we provided input on requirements and specifications for transitioning this data portal or its contents to a permanent host, which will be MarineCadastre.gov.

Recommendations for Further Research

Because GIS technology is rapidly evolving, there is further research that could be applied to these problems. As the public has become more familiar with using embedded GIS services in their mobile devices, they have become more sophisticated in consuming location-based services and have higher expectations for transparency of information. We recommend further study as to the efficacy of the CMSP process and its use in the Pacific Islands. For instance, in the permitting process, what datasets are necessary that have not been included already? Further data collection is needed to fill the data gaps. More updated information is needed on the effects of climate change such as ocean acidification, coral reef health, and changes in the distribution and populations of marine species. We recommend that coastal light imaging, detection and ranging (LiDAR) surveys be done to study the morphological changes in the coastline at a regular interval, such as every 3 years.

Marine Forces Reserve (MARFORRES)

NPS-18-M294-A: Hurricane Decision Simulator

Researcher(s): Dr. Eva Regnier, and Dr. Alejandro Hernandez Col USMC Ret.
Student Participation: No students participated in this research project.

Project Summary
Timely preparation for hurricanes is essential to both mission and personnel safety and health for the Marine Forces Reserve (MFR). This project developed, deployed and evaluated the Hurricane Decision Simulator (HDS), an online training tool that enables the Commander and key personnel at MFR Headquarters and other key staff to rapidly gain experience in hurricane preparation decision making in a realistic context, with hundreds of simulated storms.

The HDS decision context was modeled, and the HDS (version 0) was originally built for the MFR Headquarters in New Orleans in 2015. An online deployment was built in 2016 (v. 1.0). In 2017, the Hialeah Reserve Training Center was added as was the capability to introduce new decision contexts, and the synthetic storm generation model was updated (v. 2.0). Preliminary human-subjects experiments on the impact of the HDS were conducted in 2017, and a second round is planned for later this year. In 2018, further refinements on v. 2.0 were made.

The MFR uses the HDS in its annual hurricane preparations, and the (retired) G-3 indicated that the HDS "…helps us to manage our operations more effectively both in terms of training and in readiness in the event that a hurricane hits New Orleans." The HDS has reduced the cost and increased the number of storms used in training, and focused attention on uncertainty and decision making, rather than implementation. There is also anecdotal evidence that it has improved users' understanding of National Hurricane Center forecast products.

Keywords: *hurricane, emergency operations, risk management*

Background
MFR and Marine Forces North have approximately 3,000 personnel working in New Orleans, which is highly vulnerable to hurricanes and tropical storms. Many other installations are located along the Gulf and Atlantic coasts in the southeast U.S. In order to protect the safety of personnel and their families while maintaining mission capability, the Commander and other key staff must make high-stakes decisions with lead times of up to 96 hours. False alarms can cost millions of dollars and unnecessarily risk traffic fatalities. However, the forecasts available at the relevant lead times have a high degree of multidimensional uncertainty, and forecast information changes with each forecast update. All factors have been shown to increase the difficulty of the decision problem and decrease both decision quality and the ability to learn through experience (Shanteau 1992). Prior work by Taylor (2007) shows that optimal hurricane preparation decisions are not necessarily obvious, and Regnier and Harr (2006) suggest that decision makers should sometimes wait to commit to precautions like evacuation until they receive a more accurate forecast. New Orleans is particularly vulnerable to storms whose threat is not forecast with a high probability until lead times are 48 hours or less (Regnier 2008).

Findings and Conclusions

The HDS responds to the MFR's requirement for a way to address the highly challenging decision making environment. Alternative ways to meet this requirement such as identifying recommended policies or automating recommendations as a function of a specific hurricane forecast were rejected as many key factors such as mission criticality, costs, and the timeline for implementing preparation actions change frequently, and must be balanced by the Commander and other key decision makers.

The HDS is the first and only training tool that lets users make decisions and provides realistic feedback as a function of those decisions. In order to build the tool, three elements of the problem needed to be modeled:

1. the decision context, to include key decisions and decision timeline, implementation actions, other local entities' decisions;
2. storms and their forecasts, with realistic tracks, intensities and forecast products, and quality consistent with recent NHC products; and
3. the impacts of user decisions combined with storm impacts.

In order to do this, we conducted an in-depth review of MFR hurricane preparation planning documents, including the Decision Support Matrix and the Execution Matrix, and in-depth interviews with key decision makers and implementation officers. In addition, we reviewed documentation on hurricane preparation timelines from other local entities including the City of New Orleans, local parishes, the State of Louisiana and the U.S. Army Corps of Engineers. When we implemented an additional scenario for the Hialeah Reserve Training Center, we similarly conducted an in-depth review of their decision processes with the key individuals (Christopherson, 2017). This work was the primary responsibility of a student, Captain Sean Christopherson, who received his MS in Systems Engineering based on this work.

The storm model was built using statistical techniques applied to 35+ years of historical data on North Atlantic tropical cyclones from the NHC and forecast records from the most recent five years. In addition, the NHC provided code to generate products replicating some of its most up-to-date graphical products (MacKenzie & Regnier, 2015).

The online implementation of the HDS was built by the Center for Educational Design, Development and Distribution (CED3). A storm selector which allows key staff to view characteristics of the available simulated storms and choose those that are most appropriate for tabletop exercises was also added.

The MFR has begun to use the HDS in its individual and team-based hurricane preparation exercises. Their experiences show the value of the HDS in improving MFR's hurricane preparation training and decision processes by (Regnier & MacKenzie 2018):

1. Increasing the number of simulated storms staff can experience, at lower cost: Prior to the development of the HDS, MFR headquarters had two table top exercises per year in which staff ran through simulated storms. The emergency manager had developed storms by hand, at a labor cost of approximately 30 hours. When the HDS was used in the tabletop exercise in 2016, they were able to run through two storms instead of just one, increasing the number of storms experienced. The HDS also allows staff to experience storms on an individual basis at the rate of one storm every ten minutes, approximately.
2. Focusing training on uncertainty and ambiguity inherent in the decision process: According to the G-3, "...in 2015 ... the exercise focused more on reviewing operations and the timeline in our decision support matrix. This year, with the simulator, we focused the exercise more on the difficult decisions and how the uncertainty and ambiguity reflects real-life situations. As the

simulator demonstrates, a hurricane does not often follow the Marines' desire for concise planning." (Mantzel, 2016); and

3. Improving MFR personnel's understanding of the forecast products: There are many NHC products and some of them are commonly mis-interpreted by users (Pierre-Louis, 2018). Anecdotal evidence indicates that the use of the HDS improved staff's interpretation of the NHC products: ""We tend to view the forecast with the shaded cone as certain, meaning that we think the storm will never move outside the shaded cone. Relying completely on the cone gives a false sense of security because if New Orleans is outside of the cone, we might think New Orleans is safe. But the hurricane can deviate outside of that cone, and destructive weather can occur outside the cone" (Mantzel, 2016).

Recent hurricanes Michael and Florence, both threatened multiple Department of Defense (DoD) installations. They are a reminder that the importance of good hurricane preparation, and therefore informed hurricane preparation decision-making will only increase in the future. It is anticipated that the HDS will continue to be used and to be helpful to the MFR in managing their emergency operations in preparation for a hurricane.

> "The Hurricane Decision Simulator provides the Marines with an important tool that we will continue to use to practice our preparation for hurricane... The simulator helps us to manage our operations more effectively both in terms of training and in readiness in the event that a hurricane hits New Orleans." (Mantzel, 2016).

Recommendations for Further Research

We have conducted preliminary human-subjects experiments in 2017 that indicated that users' decisions are affected by the use of the HDS, in particular that users are more likely to postpone decisions or shelter in place, rather than evacuating early, after they have had experience using the HDS.

In FY18 we have designed further human-subjects experiments to estimate the effect of experience using the HDS on decisions regarding hurricane preparation decisions. These are planned for later in CY18.
Other further developments that would be valuable include:

- Extending the HDS to additional locations such as MFR Training Centers in Tampa and Galveston, as well as other organizations, such as other Marine Commands and other federal entities,
- Ongoing updating the HDS storm model to include the most recent forecast products, and
- Studying the impact of the HDS on intuitive estimations of the value of preserving flexibility by delaying irreversible decisions (such as evacuation) that may apply more generally to dynamic decisions under uncertainty.

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List of Abbreviations and Acronyms

3D - three-dimensional
3LE - three-line element
A2 - anti-access
A2AD - anti-access and area denial
ACE - Adverse Childhood Experiences
ACE - air combat element
ACINT - acoustic intelligence
ACTUV - ASW Continuous Trail Unmanned Vessel
ADA - Airfield Damage Assessment
ADC - analog-to-digital converter; conversion
ADR - Airfield Damage Repair
AEM - Adobe Enterprise Manager
AFP - adaptive force package
AFP - Armed Forces of the Philippines
AFSPC - Air Force Space Command
AI - artificial intelligence
AIS - Automatic Information System
AMSRR - Aircraft Maintenance/Supply Readiness Report
AoA - analysis of alternatives
AOR - area of responsibility
AOU - area of uncertainty
AP - automated player
APAN - All Partners Access Network
API - application program interface
APM - aircrew performance measurement
AR - augmented reality
ARA - Argentine Navy
ARC - augmented reality cued
ARL - aft RAS lane
ASBM - anti-ship ballistic missile
ASCM - anti-ship cruise missile
ASOM - Assault Support Optimization Model
ASuW - anti-surface warfare
ASW - anti-submarine warfare
ATR - automatic target recognition
AUVs - autonomous underwater vehicles
B* - best-first graph search algorithm
BAMM - Big Area Additive Manufacturing
BAMS - broad area maritime surveillance
bbls - barrels
BD - big data
BDAA - Big Data Architectures and Analytics
BDBA - big data and business analytics
BDP - Big Data Platform
BIP - Binary Integer Programming solvers
BMAs - battle management aids
BPL - broadband over power lines
BPTF - Blossom Point Tracking Facility
C N A - computer network attack
C2 - command and control
C3 - command, control, and communications
C4ISR - command, control, communications, computers, intelligence, surveillance and reconnaissance
CAC - Common Access Card
CAD - computer-aided design
CADE - Cost Assessment Data Enterprise
CAE - computer assisted exercise
CAPTCHA - completely automated public Turing test to tell computers and humans apart
CASS - Comprehensive Acoustic System Simulation
CAW - computer aided wargame
CDET - College of Distance Education and Training
CDOE - California Department of Education
CEC - Collaborative Engagement Capability
CENSECFOR - Center for Security Forces
CENTCOM - United States Central Command
CER - cost estimating relationship
CFT - combat fitness test
CG18 - Cobra Gold 18
CGA - Common Ground Architecture
CHAMP - Counter-electronics High-powered Advanced Missile Project
CIRPAS - Center for Interdisciplinary Remote Piloted Aircraft Study
C-ISR - counter-intelligence, surveillance, and reconnaissance
CIV - civilian
CIV INT - civilian intern
CLF - Combat Logistics Force
CMI - combat marksmanship instructor
CMS - Content Management System
CMSP - coastal marine spatial planning
CNMI - Commonwealth of the Marianas Islands
CNN - convolutional neural networks
CNO - Chief of Naval Operations
CNO - Chief of Naval Operations
CNP - Chief of Naval Personnel
COE - Concept of Employment
COI - community of interest
COIN - Common Operator Interface for NSCT1
COLREGS - Collision Regulations
COMNAVSURFOR - Commander, Naval Surface Forces
CONOPS - concept of operations
COP - common operational picture

LIST OF ABBREVIATIONS AND ACRONYMS CONT.

CORE - common operational research environment
COTS - commercial off-the-shelf
CoV - coefficient of variation
CRADA - Cooperative Research and Development Agreement
CRUDES - Cruiser/Destroyer
CSV - comma-separated values
CTAP - common tactical air picture
CTF - Commander, Task Force
CTF-73 - Task Force 73/Commander, Logistics Group Western Pacific
CV - computer vision
CVL - light aircraft carrier
CVN - nuclear aircraft carrier
CVW - carrier air wing
DARPA - Defense Advanced Research Projects Agency
DDG - Guided Missile Destroyer
DE - directed energy
DEOMI - Defense Equal Opportunity Management Institute
DevOps - Development Operations
DFL - digital flashing light
DFM - Diesel Fuel Marine
DG - Digital Globe, Inc.
DISA - Defense Information Systems Agency
DL - distributed lethality
DMO - distributed maritime operations
DMS - Dynamic Modularity from Sea
DNF - Dynamic Network Flow
DoD - Department of Defense
DoDAF - Department of Defense Architecture Framework
DOE - data farming and design-of-experiments
DoN - Department of the Navy
DPB - data science, predictive analytics, and big data
DSAID - Defense Sexual Assault Incident Database
DSRA - Dry-docking Selected Restricted Availability
DSSM - Deck Simulating Shock Machine
DT - Design Thinking
DTL - Disruptive Technology Laboratory
E.O. - executive order
EAPF - expanded adaptive force package
EFFBD - enhanced functional flow block diagrams
EM - electromagnetic
EO - electro-optical
EOC - Emergency Operations Center
EOY - End-of-Year
ExMCM - Expeditionary Mine Counter Measures
EXWC - Engineering and Expeditionary Warfighting Command
F-35B - Lightning II Joint Strike Fighter STOVL variant
FAA - Federal Aviation Federation
FABLABS - fabrication labs
FAC - Fast Attack Craft
FEM - finite element method
FEVS - Federal Employee Viewpoint Survey
FFDB - functional flow block diagram
FIAC - Fast Inshore Attack Craft
FIFO - first-in-first-out
FITREPs - Fitness Report; fitness reports
FLC - Fleet Logistics Center
FLIR - Forward Looking Infrared
FLoE - Functional Lines of Effort
FOR - field of regard
FOUO - For Official Use Only
FOV - field of view
FPGA - Field Programmable Gate Array
FRL - forward RAS lane
FSCM - Fire support coordinating measure
FSP - floating shock platform
FSST - full ship shock trial
FTF - first to fire
GAMS - General Algebraic Modeling System
GAO - Government Accounting Office
GCE - ground combat element
GIS - Geographic Information System
GPS - Global Positioning System
GUI - graphical user interface
HDFS - Hadoop Distributed File System
HDS - Hurricane Decision Simulator
HEL - high energy laser
HELIOS - High Energy Laser with Integrated Optical Dazzler and Surveillance
HIS - human systems integration
HR - human resources
HTL - human-in-the-loop
IBMCS - Information Battle Management and Control System
ICAO - International Civil Aviation Organization
IE - information environment
IE Ops - Information Environment Operations

LIST OF ABBREVIATIONS AND ACRONYMS CONT.

IEEE - Institute of Electrical and Electronics Engineering
IFF - identification friend or foe
II MEF - II Marine Expeditionary Force
ILS - integrated logistics support
IMO - International Maritime Organization
IOSS - Integration and Operation Support System
IP - information problem
IP - Internet Protocol
IPOE - intelligence preparation of the operational environment
IPv4 - Internet Protocol, version 4
IPv6 - Internet Protocol, version 6
IR - incident response
IRB - Institutional Review Board
iRTT - initial round trip time
ISLS - Inter-Satellite Links
ISO - International Standardization for Organization
ISR - intelligence, surveillance, and reconnaissance
ITACS - Information Technology and Communications Services
ITB - Infantry Training Battalions
IW - information warfare
JCA - Joint Campaign Analysis
JCS - Joint Chiefs of Staff
JDL - Joint Data Laboratories
JIATF-S - Joint Interagency Task Force-South
JIFX - Joint Interagency Field Experimentation
JNLWP - Joint Non-Lethal Weapons Program
JP-5 - jet engine grade fuel
JTLS - Joint Theater Level Simulation
JTLS GO - JTLS Global Operations
JULLS - Joint Universal Lessons Learned System
KB - Knowledge Base
LaWS - Laser Weapon System
LCE - Logistics Combat Element
LCS - littoral combat ship
LCU - landing craft, utility
LDUUV - Large Diameter Unmanned Underwater Vehicle
LED - light emitting diode
LEO - Low Earth Orbit
LFT&E - live fire test & evaluation
LHA - amphibious assault ship (general purpose)
LiDAR - light detection and ranging
LiFi - light fidelity
LITMUS - Lightweight Interstitials Toolbox for Mission Engineering Using Simulation
LLA - Lexical Link Analysis
LLP - Lessons Learned Program
LOS - Line of Sight
LP - linear programming
LPD - landing platform/dock
LRM - long-range missile
LRS - Learning Record Store
LWSM - Light Weight Shock Test Machine
MACS - MEU Amphibious Connector Scheduler
MAGTF - Marine Air-Ground Task Force
M-AM - metal additive manufacture
MarineNet - Marine Corps Distance Learning Network
MAT-MP - Modular Advanced Technology-Marksmanship Proficiency Toolkit
MAWG - MOVES Research Working Group
MBSE - model-based systems engineering
MC-DL-RASM - Dual Lane Replenishment at Sea model
MCLOG - Marine Corps Logistics Operations Group
MCM - mine countermeasures
MCMC - Markov chain Monte Carlo
MCNEL - Marine Corps Network Efficiency Lab
MDA - Maritime Domain Awareness
MD-BPP - multi-dimensional bin packing problem
MDUSV - Medium Displacement Unmanned Surface Vessel
MDUUV - Medium Diameter Unmanned Underwater Vehicle
ME - mission engineering
MEA - mission engineering and analysis
MEB - Marine Expeditionary Brigade
MEDAL - Mine Warfare Environmental Decision Aid Library
MEF - Marine Expeditionary Force
MEMS - micro-electro-mechanical system
MEU - Marine Expeditionary Unit
MFR - Marine Forces Reserve; Marine Corps Forces Reserve
MH-60S - Multi-Mission Helicopter
MIG - MEF Information Group
MIW - mine warfare
ML - machine learning
MLA&E - Mission Level Architecture Engineering
MNF - multinational force

MNMV - My Next Move for Veterans
MOEs - measures of effectiveness
MOPs - measures of performance
MOS - Minimum Operating Strip
MSC - Military Sealift Command
MSP - Maritime Security Program
MSST - Master Scheduling Support Tool
MUOS - Mobile User Objective System
MUX - Marine Corps Unmanned Experimental tiltrotor system
MV - Multi-Mission Vertical and/or Short Takeoff and Landing
MWSM - medium weight shock machine
MXSA - Model Exchange Staging Area
N2/N6 - DCNO for Information Warfare
N3/N5 - DCNO for Operations, Plans and Strategy
N50 - OPNAV Strategy Division
N51 - OPNAV Strategy and Policy Division
N7 - DCNO for Warfare Requirements and Programs
N82 - Director, Fiscal Management Division
N84 - Director, Innovation, Test and Evaluation, and Technology Requirements
N9 - DCNO for Warfare Systems
N97 - DCNO for Warfare Systems, Director for Undersea Warfare
NAVAIR - Naval Air Systems Command
NAVIFOR - Naval Information Forces
NAVSEA - Naval Sea Systems Command
NDLAs - Navy Desired Leader Attributes
NGO - non-government organization
NIFC-CA - Navy Integrated Fire Control - Counter Air
NIH - National Institutes of Health
NLLS - Navy Lessons Learned System
NLWs - non-lethal weapons
NMCI - Navy Marine Corps Intranet
NMCS - not mission capable supply
NOC - National Ocean Council
NOLH - Nearly Orthogonal Latin Hypercube
NOSQL - Not Only Structure Query Language
NOW - Network Optional Warfare
NP - non-deterministic polynomial-time
NPS - Naval Postgraduate School
NPSAT1 - Naval Postgraduate School Satellite 1
NRDE - Naval Research and Development Enterprise
NRP - Naval Research Program
NSA - National Security Affairs
NSWC - Naval Special Warfare Command
NSWC - Naval Surface Warfare Center
NTM - National Technical Means
O*NET - Occupational Information Network
OccFld - Occupational Field
OLDS - Operational Littoral Defense System
ONR - Office of Naval Research
OODA - Observe, Orient, Decide, and Act
OPAREAS - operating areas
OPNAV - Office of the Chief of Naval Operations
OPSEC - operational security
OSD CAPE - Office of the Secretary of Defense for Cost Assessment and Program Evaluation
OTA - Other Transitional Authority
PCAPNG - packet capture next generation
PEO IWS - Program Executive Office, Integrated Warfare Systems
PET - performance evaluation transformation; Performance Evaluation Transformation
PFT - physical fitness test
PI - principal investigator; Principal Investigator
PIM - position of intended movement
PIRPB - Pacific Islands Regional Planning Body
PLA(N) - People's Liberation Army Navy
PLC - power line communication
PMCS - partial mission capable supply
PMOS - primary military occupational specialty
POL - pattern of life
POSSUB - unplanned interruptions
PPLI - Precision Participation Location Identifier
PPT - Position and Partials as a function of Time
PPT3 - Position and Partials as a function of Time v3
PROCONS - professional and conduct scores
RAMS - Rapid Assessment Marksmanship System
RAPIER - Rapid Image Exploitation Resource
RAS - replenishment at sea
REA - Running Estimate Architecture
RES - Reduction Expansion Synthesis
ROI - return on investment
ROME - Repair Optimization Materiel Evaluator
SA - systems analysis
SA - Situational Awareness
SAGs - surface action groups
SAPRO - Sexual Assault Prevention and Response Office

List of Abbreviations and Acronyms Cont.

SAR - synthetic aperture radar
SAS - synthetic aperture sonar
SATVUL - Satellite Vulnerability
SBLDSS - Sea-Based Logistics Decision Support System
SCM - supply chain management
SCS - South China Sea
SDP - semi-definite programming
SDS - Ship Detection System
SE - systems engineering
SEA HUNTER - experimental autonomous unmanned vessel
SEACAT - Southeast Asia Cooperation and Training
SEED - Simulation Experiments and Efficient Designs
SEM - scanning electron microscopy
SIGS - School of International Graduate Studies
SM6 - Standard Missile 6AAAA
SMEs - subject matter experts
SN - Singapore Navy
SNOPT - Sparse Nonlinear OPTimizer
SOC - Standard Occupational Classification
SoI - system of interest
SoS - system of systems
SPAWAR - Space and Naval Warfare Systems Command
SPOTR - Surveillance, Persistent Observation and Target Recognition
SQL - Structured Query Language
SQP - sequential quadratic programming
SRDR - Software Resources Data Report
SRR - Strategic Readiness Review
SSC Pacific - SPAWAR Systems Center Pacific
SSL - solid state laser
SSL-TM - Solid State Laser Technology Maturation
STK - Satellite Tool Kit
STS - sociotechnical system
SUUV - Small Unmanned Underwater Vehicle
SUW - surface warfare
SWAP-C - size, weight, power, and cooling
SWAT - special weapons and tactics
SWO - surface warfare officer
T&R - training and readiness
TA - thermoviscous acoustic
T-AKE - dry cargo/ammunition ship
TAMCN - Table of Authorized Material Control Numbers
T-AO - fleet replenishment ship
TAO - Tactical Action Officer
T-AOE - fast combat support ship
TASW - theater anti-submarine warfare
TC - traditionally cued
TCP - Transmission Control Protocol
TCPED - Tasking, Collection, Processing, Exploitation, and Dissemination
TECOM - Marine Corps Training and Education Command
TEMPEST - Telecommunications Electronics Material Protected from Emanating Spurious Transmissions
TFDW - Total Force Data Warehouse
TLE - two-line element
TSOA - Tactical Service Oriented Architecture
UAS - unmanned aerial system
UAV - unmanned aerial vehicle
UCB - upper confidence bound-
UN - United Nations
UNDEX - underwater explosion
USA - United States Army
USAVs - unmanned autonomous surface vessels
USFF - U.S. Fleet Forces Command
USINDOPACOM - United States Indo-Pacific Command
USMC - United States Marine Corps
USN - United States Navy
USNS - United States Naval Ship
USSR - Union of Soviet Socialist Republics
USV - unmanned surface vehicle
UUV - unmanned underwater vehicle
UWSNs - underwater sensor networks
UXO - unexploded ordinance
UxV - unmanned vehicle
VaR - value at risk
VE - virtual environment
VIP - Vehicle Interface Program
VLS - vertical launching system
VMM - Marine medium tiltrotor
VOI - vessel(s) of interest
VR - virtual reality
WCDMA - Wide Code Division Multiple Access
WEB3D - interactive 3D content embedded into web pages
WESTPAC - Western Pacific
WSNs - wireless sensor networks
X3D - Extensible 3D
xAPI - Experience API

List of Abbreviations and Acronyms Cont.

XLUUV - Extra Large Unmanned Underwater Vehicle
XML - eXtensible Markup Language
YOS - years of service

NAVAL RESEARCH PROGRAM
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