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MESSAGE FROM THE DEAN OF RESEARCH

I have been pleased to support the Naval Postgraduate School (NPS) Naval Research Program (NRP) since its humble beginnings in FY14. The studies sponsored within FY21 have made significant contributions to the Department of the Navy by providing insights to key operational problems that decision-makers face along with recommendations to support cost savings in a fiscally constrained environment. The NRP’s program goals and execution support the Chief of Naval Operations vision of NPS as the Navy’s applied research university. The interactions, experiences and knowledge gains that occur here are unique; it would be difficult to replicate them anywhere else in the world, which makes NPS an invaluable Fleet asset.

This report highlights results from the spectrum of NRP research activities conducted on behalf of both Navy and Marine Corps Topic Sponsors during the 2021 fiscal year. Executive summaries from the research projects are included in the report. While most of those summaries detail final results and recommendations for further research, some projects have multi-year project lengths. In those cases, progress-to-date is reported.

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

Finally, the many benefits that accrue through the NRP depend on the wholehearted participation of NPS faculty, students, and the many Topic Sponsors from across Navy and Marine Corps headquarters commands. As I will be rotating out of this role with the end of this program year, I especially want to pass along my thanks to all who have participated this year and since the program’s inception in 2014.

Sincerely,

[Signature]

Dr. Jeffrey Paduan, Outgoing NPS Dean of Research
Table of Contents

Message From the Dean of Research .......................................................................................................................... i

Naval Research Program Overview ............................................................................................................................. 1
  Background ............................................................................................................................................................... 1
  Organization ............................................................................................................................................................ 1
  Mission and Goals .................................................................................................................................................. 2
  Program Administration .......................................................................................................................................... 2
  Accomplishments .................................................................................................................................................... 3

ASN(RDA) - Research, Development, and Acquisition ............................................................................................... 4
  NPS-21-J218-A: Long Range Unmanned Surface Vessel ......................................................................................... 4
  NPS-21-N064-A: All-Domain Sensor Network Orchestration from Seabed-to-Space .............................................. 6
  NPS-21-N091-A: Information Warfare in the High End Fight .................................................................................. 9
  NPS-21-N282-A: Operational Analysis and CONOPS Definition for Next Gen Mine Warfare .................. 14
  NPS-21-N307-A: The Integration of Reliability, Availability, and Maintainability (RAM) into Model-Based Systems Engineering (MBSE) .............................................................................................................. 17
  NPS-21-N348-A: MQ-25 Manned/Unmanned Teaming (MUM-T) .................................................................. 24
  NPS-21-N387-A: Weapon Systems Safety When Deploying AI Technology ...................................................... 28
  NPS-21-N392-A: Commercial Batteries for Navy Use (Continuation) .................................................................. 31

N1 - Manpower, Personnel, Training & Education .............................................................................................................. 32
  NPS-21-N298-A: Evaluating the Effectiveness of Blended Learning Strategies in Navy Training .... 32
  NPS-21-N299-A: Mobile Learning Technology: Assessment and Recommendations ............................... 35
  NPS-21-N315-A: Assessing Inclusion Behaviors and Impact of Inclusion within the Fleet ....................... 37
  NPS-21-N330-B: Nuclear Officer Bonus & Incentive Pay (NOBIP) and Retention ........................................ 40
  NPS-21-N333-A: Evaluation of Leadership Traits for Future Warfare ............................................................ 43
  NPS-21-N351-A: Social Network Analysis on Connectedness, Destructive Behaviors, and Effects on Stress ........................................................................................................................................ 45

N2/N6 - Information Warfare ........................................................................................................................................... 49
  NPS-21-N037-A: Cyber Warfighting System for Resilience and Response ..................................................... 51
  NPS-21-N055-A: Global Search for High-Value Extended-Range Forecast Products .................................. 53
  NPS-21-N124-A: Leveraging Commercial and Other Innovation for Future USN Data, Information, and Intelligence Needs [NECC Focus] ........................................................................................................... 56
  NPS-21-N186-A: Subseasonal to Seasonal (S2S) Forecasting of Tropical Cyclones .................................. 58
  NPS-21-N260-A: Machine Learning (ML) for Signal Detection ................................................................. 61
  NPS-21-N342-A: Battle Management Aids: Leveraging Artificial Intelligence for Tactical Decisions .... 64
  NPS-21-N372-A: DMO Tactical Grid – Edge Processing, Mission Analytics, Officer Qualification .................. 68
  NPS-21-N373-A: Business Intelligence for Expeditionary Advanced Base Operations (EABO) Shaping Flexible C2 Organizational Structure .............................................................................................. 68

N3/N5 - Plans & Strategy ............................................................................................................................................... 73
  NPS-20-N307-A: China’s Strategic Modernization in a Post-INF Treaty World ............................................ 75
  NPS-21-N177-B: Prospects for Deterrence, Escalation, Coercion and War in the Indo-Pac (Cont.) .......... 78
Table of Contents Cont…

NPS-21-N290-A: The Battle of the Atlantic/Arctic in the Present and Future: Policy, Strategy and Operational Aspects for Crisis and War ................................................................. 82

N4 - Fleet Readiness & Logistics ................................................................................................................................. 84
NPS-21-N014-A: COTS Microgrids for Sustainable Energy Integration and Resiliency ........................................ 84
NPS-21-N030-A: A Cost Benefit Analysis of Transitioning the USN to a Single Fuel Type ........................................ 87
NPS-21-N057-A: Deep Analytics for Readiness Impacts of Underfunding Spares Backlogs .......................... 89
NPS-21-N104-A: Warfare Analysis of Contested Logistics Agility ........................................................................ 93
NPS-21-N104-B: Naval Logistic Network for The Great Power Competition and Operation in Contested Environment ......................................................................................................................... 95
NPS-21-N332-A: Blockchain and AI Technology in Support of Transparent Navy Logistics and Global Supply Chains (Continuation) ......................................................................................................................... 98
NPS-21-N355-A: Evaluating Performance of Directional Sensors in Support of Detecting and Tracking Targets of Interest in Real Ocean Environments ................................................................. 101

N7 - Warfighting Development .................................................................................................................................................. 105
NPS-21-N105-C: Shoot, Move and Communicate – Increasing NSW Mission Effectiveness through AI/ML Augmented Unmanned Systems ........................................................................... 105
NPS-21-N105-E: Bento Box—Modular/Recoverable Stratospheric Balloon Payload to Enable Artificial Intelligence for Small Unit Maneuver ................................................................................................. 107
NPS-21-N105-F: Predicting Effectiveness of Human-Machine Teaming ...................................................................... 111
NPS-21-N113-B: Mapping and Analyzing NSW’s Blue Network to Leverage Insights for a Competitive World ................................................................................................................................................. 117

N8 - Integration of Capabilities & Resources ...................................................................................................................... 120
NPS-21-N031-A: Applying Design of Experiments to Improve Campaign Analysis with the Synthetic Theater Operations Research Model ........................................................................................................... 120
NPS-21-N115-A: Optimization of Engine Readiness Assessment Model (EDRAM) ............................................... 124
NPS-21-N117-A: Optimization of Airframe Depot Readiness Assessment Model (ADRAM) ........................................ 125
NPS-21-N173-A: VLS Missile Mix, Firing Policy, and Deterrence Against Red Salvos ............................................ 128
NPS-21-N180-A: Warfighting Readiness PESTONI Study ................................................................................................. 131
NPS-21-N368-A: Optimizing Large Financial Portfolios ................................................................................................. 133

N9 - Warfare Systems ......................................................................................................................................................... 134
NPS-21-N107-A: Operationalizing Naval Special Warfare (NSW)/Special Operations Forces (SOF) for the Countering Weapons of Mass Destruction (CWMD) Mission ......................................................................................................................... 137
NPS-21-N109-A: In-Depth Analysis of Evaluation Practices and Criteria for Competency-Based Aviation Training Models ......................................................................................................................... 140
NPS-21-N114-A: Modeling SIGINT ................................................................................................................................. 143
NPS-21-N210-B: Unmanned Carrier Concept in Support of DMO .................................................................................. 146
NPS-21-N295-B: Integration of MDUSV into a Carrier/Expeditionary Strike Group ...................................................... 150
NPS-21-N359-A: Mine Warfare in Great Power Competition ................................................................................................. 152

U.S. Fleet Forces Command (USFF) ................................................................................................................................. 155
NPS-21-J087-A: DMO Tactical Grid – Edge Processing, Mission Analytics, Officer Qualification ......................................................................................................................................................... 155
NPS-21-N095-A: Employing Machine Learning to Predict Student Aviator Performance (Cont.) ................................. 156

Naval Postgraduate School Naval Research Program FY21 Annual Report
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPS-21-N135-A: Information Warfare Force and Systems Readiness Assessment</td>
<td>158</td>
</tr>
<tr>
<td>NPS-21-N167-A: Medical Supply Chain Impacts of Pandemic Preparedness and Response</td>
<td>159</td>
</tr>
<tr>
<td>NPS-21-N188-A: Analysis: How to Rapidly Bring Hypersonic Missile Capability to the Surface Fleet</td>
<td>162</td>
</tr>
<tr>
<td>NPS-21-N213-A: Quantifying, Visualizing, and Tracking Capability Gaps</td>
<td>165</td>
</tr>
<tr>
<td>NPS-21-N263-A: High Data Rate HF Communications for BFTN using Advanced Waveform Techniques</td>
<td>167</td>
</tr>
<tr>
<td>NPS-21-N264-A: Joint Fires Seabed Warfare</td>
<td>169</td>
</tr>
<tr>
<td>NPS-21-N281-A: Navy Expeditionary Additive Manufacturing (AM) Capability Integration</td>
<td>171</td>
</tr>
<tr>
<td>NPS-21-N263-A: High Data Rate HF Communications for BFTN using Advanced Waveform Techniques</td>
<td>167</td>
</tr>
<tr>
<td>NPS-21-N264-A: Joint Fires Seabed Warfare</td>
<td>169</td>
</tr>
<tr>
<td>NPS-21-N281-A: Navy Expeditionary Additive Manufacturing (AM) Capability Integration</td>
<td>171</td>
</tr>
<tr>
<td>HQMC Aviation (AVN)</td>
<td>174</td>
</tr>
<tr>
<td>NPS-21-M140-A: Analysis of Alternative UAV Technologies to Support Next-generation UAV</td>
<td>174</td>
</tr>
<tr>
<td>HQMC Combat Development and Integration (CD&amp;I)</td>
<td>177</td>
</tr>
<tr>
<td>NPS-21-M133-A: An Integrated Framework to Develop and Analyze Concepts of Employment for Surface Connectors</td>
<td>177</td>
</tr>
<tr>
<td>NPS-21-M238-A: Efficiently Using Families of Diverse Models to Better Inform Decision Makers in Objective and Repeatable Ways</td>
<td>180</td>
</tr>
<tr>
<td>HQMC Deputy Commandant Information (DCI)</td>
<td>184</td>
</tr>
<tr>
<td>NPS-21-M006-B: Automated Cyber Operations Data Mission Replay</td>
<td>184</td>
</tr>
<tr>
<td>NPS-21-M072-A: 5G for Field Expedition C2 Centers</td>
<td>186</td>
</tr>
<tr>
<td>HQMC Installations and Logistics (I&amp;L)</td>
<td>189</td>
</tr>
<tr>
<td>NPS-21-M159-A: An Analysis of Repairable Items Lead Times at USMC Wholesale ICP</td>
<td>189</td>
</tr>
<tr>
<td>HQMC Manpower and Reserve Affairs (M&amp;RA)</td>
<td>192</td>
</tr>
<tr>
<td>NPS-21-M035-A: Understanding Motivational Factors of Problematic Video Gaming in the USMC and USN</td>
<td>192</td>
</tr>
<tr>
<td>HQMC Plans, Policies &amp; Operations (PP&amp;O)</td>
<td>196</td>
</tr>
<tr>
<td>NPS-21-M319-A: Cognitive Assistance with AI COAs: Radical Rethinking of HMT Mission Workflows and Decision Making as AI Assumes a Peer Relationship with Operators</td>
<td>199</td>
</tr>
<tr>
<td>HQMC Programs &amp; Resources (P&amp;R)</td>
<td>202</td>
</tr>
<tr>
<td>NPS-21-M101-A: Ground-Based Anti-Ship Missile Effectiveness</td>
<td>202</td>
</tr>
<tr>
<td>NPS-21-M101-B: Optimal Munitions Mix for USMC Mobile Anti-Ship Missiles Launcher</td>
<td>205</td>
</tr>
<tr>
<td>Marine Corps Forces Command (COMMARFORCOM)</td>
<td>207</td>
</tr>
<tr>
<td>NPS-21-M181-A: Analysis of the Specifications and Capabilities for the Next-Gen LRUSV</td>
<td>210</td>
</tr>
<tr>
<td>NPS-21-M182-B: Counter-Unmanned Aerial Systems for the Navy and Marine Corps: Future Hardware Development Needs</td>
<td>211</td>
</tr>
<tr>
<td>NPS-21-M187-B: DMO Tactical Grid – Edge Processing, Mission Analytics, Officer Qualification</td>
<td>214</td>
</tr>
<tr>
<td>Marine Corps Systems Command (MARCORSYSCOM)</td>
<td>214</td>
</tr>
<tr>
<td>NPS-21-M079-B: Training Intelligent Red Team Agents Via Reinforcement Deep Learning</td>
<td>214</td>
</tr>
<tr>
<td>List of Abbreviations and Acronyms</td>
<td>218</td>
</tr>
</tbody>
</table>
NAVAL RESEARCH PROGRAM OVERVIEW

The Naval Postgraduate School (NPS) Naval Research Program (NRP) was funded by the Chief of Naval Operations and supports research projects for the Navy and Marine Corps. The 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 NRP support is through participation at the 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 to leverage the expertise and experience of NPS' interdisciplinary 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 NRP has been 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 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 NRP working groups with their own funding.

Organization

The organization of the 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. It is a continual process that begins with topic submission from the naval enterprise. Topic Sponsors and NPS faculty then collaborate at the annual convening of the NRWG at NPS each spring.

The 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 represented 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 Naval Analytic Council. 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 NRP mission is to: provide operationally relevant research experiences to NPS faculty members, provide operationally relevant thesis opportunities to NPS students, and provide useful results from research projects and studies to Topic Sponsors across the naval enterprise. The goals of the 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 reflects one of NPS’ unique contributions to the combat effectiveness of the Navy and Marine Corps by “The development of a program of defense-relevant research, encouraging a professional dialogue among students and faculty engaged in efforts to solve significant military problems. Research assures the continued relevance of NPS faculty capabilities and that the latest processes, materials, and technologies can be transferred to USN and USMC to help strengthen the Nation’s defense. (SECNAVINST 1524.2D dtd 29 April 2019),” and NPS is postured to fulfill this DoN requirement.

The process by which a research topic is identified and funded begins with convening the annual NRWG in the spring. The NRWG is a forum for communicating, reviewing, validating, prioritizing, and recommending research-topic challenges for consideration by the DoN. It provides 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. Other topic solicitation methods may be employed in coordination with the NRWG to maximize the breadth and scope of research topics.

**Program Administration**

The 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 NRP. The NRP Program Office includes a program director, deputy program director, 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 NRP Program Office coordinates and liaises with NRP designated points of contact/program area manager (PAM) counterparts from the various research sponsors.
Accomplishments

The NRP strategically illustrates both 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 in their efforts to deliver cost-efficient results to the DoN. The NRWG is one manifestation of this integration process. Since its inception, the NRWG has connected more than 286 Navy and Marine Corps organizations with NPS faculty and students for this purpose. To date, the NRP has collected over 2,700 potential and current research topics though NRWG events and funded over 640 research projects. Embedding the NRP into the fabric of the NPS strategic planning process enables the school to rapidly respond to current and future “compass swings” in naval research requirements.

As a result of the NRP’s operations, NPS research is more directly aligned with the naval community than ever before.

- Distributed $11.05M in funding, which translated into 85 (81 represented in this report) distinct U.S. Navy and Marine Corps projects that cover the entire Office of the Chief of Naval Operations (OPNAV) staff, Fleet Forces (FF), Assistant Secretary of the Navy for Research, Development and Acquisition (ASN (RDA)) and Marine Corps functional organizations.
- Mobilized the NPS faculty to focus more of their research on naval issues. More than 130 civilian/military faculty from all four academic schools joined the NRP effort, highlighting NPS’ campus-wide commitment to naval research.
- Provided opportunities for cross-campus, inter-departmental research partnerships involving nearly half of the funded projects. These partnerships provide a distinct advantage by applying integrated perspectives and that result in interdisciplinary approaches.
- Enjoyed robust student engagement, leveraging the students’ previous operational experience and newfound knowledge from graduate studies. Over 300 United States and foreign thesis students collaborated with faculty on 57 of the 81 funded projects.

*Executive summaries for two FY20 projects are included in this annual report but are not reflected in the FY21 Annual Report statistics.*
ASN(RDA) - RESEARCH, DEVELOPMENT, AND ACQUISITION

NPS-21-J218-A: Long Range Unmanned Surface Vessel

Researchers: Dr. Fotis Papoulias, Dr. Jarema Didoszak, and Dr. Joseph Klamo
Student Participation: Total Ship Systems Engineering (TSSE) Program students - LT Edward Anuat USN, LT Gladys Anuat USN, LT Kyle Diatte USN, LT Zachary Everhart USN, LT Alexander Fedorovich USN, LT Samuel Royster USN, and LT James Wickham USN

Project Summary
Within the next five years, the U.S. Marine Corps is expecting to field the first generation long range unmanned surface vessel (LRUSV) as part of its mission support element in the littorals. Introduction of this new type of autonomous support system serves to bring extended intelligence, surveillance, and reconnaissance functionality as well as greater lethality against sea and land targets in a compact yet highly capable surface vessel. While the Naval Operational Architecture outlined in the Unmanned Campaign Framework drives rapid accreditation and fielding, it also provides an opportunity for greater system optimization through examination of a system-level design space. This study analyzes the LRUSV in terms of platform engineering requirements balanced against mission performance and overall systems integration. Design parameter sensitivities related to payload, speed, and range are compared and recommendations are proposed for future generations of the LRUSV system architecture.

Keywords: unmanned surface vessels, USVs, long range unmanned surface vessel, LRUSV, hydrodynamics, trade studies

Background
Unmanned surface vessels (USVs) will play a vital role in the future U.S. Navy and U.S. Marine Corps strategy. These vessels will be equipped with a variety of sensors and weapons and will be able to operate unmanned or minimally manned as part of a hybrid seaborne solution. Likewise, they will deploy autonomously or be controlled remotely by human operators. One example of such a vessel is the long range unmanned surface vessel (LRUSV) for the Marine Corps. Although the importance of such vessels for future operations is readily acknowledged, the optimal shape, size, missions, and control of these vessels are yet unknown. Rapid introduction into the fleet through experimentation and rapid fielding will aid in their acceptance and integration but not necessarily advance the understanding of the right size, form, and fit.

Naval architects have long struggled to design ships and other seagoing craft that find the delicate balance between stakeholders’ desires and the fundamental constraints imposed by the laws of physics. To address this required balance, the complex dependencies of system requirements as tied to system parameters must be explored within the overall design space. An opportunity exists to marry the unique mission needs of the LRUSV with unmanned vessel design in advancing early-stage ship design practices using digital engineering.
The goal of this project is to determine the overall impact in considering various design tradeoffs between operational capability drivers and hull parameters. It is predicted that early incorporation of operational factors and an ability to interactively adapt the design based on operational inputs from experienced operators will produce a more robust and operationally sound product. Furthermore, this will reduce detailed design rework, shortening the overall design-acquisition timeline. First, we determine the operational mission requirements for the vessel. Next, a more detailed analysis is conducted to establish which of these primary factors will most heavily impact the vessel hull, mechanical design, and electrical design. Consideration will also be given to the timing for the insertion of operational modeling results into an early-stage design. Strict adherence to digital engineering fundamentals must be utilized to ensure overall design cohesion.

Findings and Conclusions
The LRUSV is envisioned as “an unmanned platform capable of traveling autonomously for long distances and launching loitering munitions to address sea and land targets” (Marine Corps Systems Command, 2020). The current production version is based on the Navy’s “Defiant” 40PB which is a twin Cummins QSB 6.7 diesel waterjet propelled, semi-planning hull patrol boat, manufactured by Metal Shark. It has a 40-knot sprint speed and 10-15 knot service. The desire to quickly field a working vessel has provided an excellent opportunity to further investigate the design parameters alongside field testing of this early production unit.

Some of the primary design variables for any platform are the desired payload, range, and forward speed. In conjunction with specific fuel consumption and overall loading conditions, they form a design space that can be used to quantify decision tradeoffs. Investigations using craft velocity versus range were conducted to explore payload throughput. Non-dimensional analyses were used to provide figure of merit results throughout the design space. From this, an optimum speed-range combination with respect to the selected measure of merit was observed. For a given range, higher or lower speeds than its optimum value result in lesser performance, that is fewer tons per hour. Similarly, for a given speed, there appears to be an optimum range as well. The sensitivity of these results was evaluated as a function of propulsion system efficiency. As expected, the optimum band shifts to higher speed-range combinations. Payload sensitivity was also studied and resulted in findings that showed that for a more lightly loaded vessel, the benefits of propulsion system efficiency diminished exponentially as a function of range. However, in the case of both a higher loading fraction and a higher efficiency propulsion system, the optimum band shifts up and in fact, it approaches that of a linear system; in other words, twice the speed results in approximately twice the payload throughput.

Recommendations for Further Research
Operator-reported observations from in-service use regarding the platform form factor suitability and functionality can be integrated with these design space findings to inform future models.

Based on the results of this study, the following recommendations for further research can be drawn. First, higher fidelity sensitivity analysis of various design parameters based on updated information of vehicle characteristics must be performed. Previous results can be used to identify the most sensitive regions of design parameters and their values.
Based on the results of the sensitivity analysis, a set of recommendations will be obtained that can be used
to quantify and guide decision-makers for optimum vehicle employment. Finally, we can extend the study
to encompass the small unmanned surface vessel which is proposed as a modular capability that is to
interoperate as a component of the long range unmanned surface vessel system.

References
(MARCORSYSCOM Notice M67854-21-I-1820).
https://sam.gov/opp/ac49b85912f144cb8d1546f104af05b9/view

NPS-21-N064-A: All-Domain Sensor Network Orchestration from Seabed-to-
Space

Researchers: Dr. James Scrofani, Dr. Jihane Mimih, and Mr. Edward Waltz
Student Participation: No students participated in this research project.

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

The study modeled and evaluated the role of space constellations for sensing and network relay to enable
over-the-horizon ISRT. Our findings show that conceptual coordination of seabed-to-space sensors via
the planned DOD low-earth orbit space constellation relay is feasible and enables DMO over-the-horizon
operations for the stressful surface warfare scenario. We have also shown that although the orchestration
of the diverse sensors from seabed tip-off to space sensing to perform coordinated fires is complex, it is
feasible when space relay constellations demonstrate high availability. For example, our study has shown
that a constellation like the planned DOD Space Development Agency constellation as modelled, or
larger, will provide coverage to enable distributed search, detection, and tracking but may require local
unmanned air and surface vehicles’ support for terminal engagement. We recommend the next step in
analysis is a simulation of a wider range of cases with dynamic maritime scenarios and a range of
constellation parameters and sensors.
Keywords: maritime domain awareness; MDA; distributed maritime operations; DMO; seabed-to-space; AI; artificial intelligence; CIRs; Commander’s Intelligence Requirements; C5ISRT; command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting; DOD; Department of Defense; ISR; intelligence, surveillance, and reconnaissance; ISRT; intelligence, surveillance, reconnaissance and targeting; IP; internet protocol; JADC2; joint all-domain command and control; LEO; low-Earth orbit; ML; machine learning; TCP; transmission control protocol

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

An all-domain sensor orchestrator must consider all feasible collection combinations over some time horizon against all targets and then optimize the assignment of sensors-to-targets over time. Optimization requires an objective function—the expected value of each feasible set of collections at each set of collection times. The definition of this expected value must be developed, and the practical optimization approach (algorithms) must be chosen for such a wide range of options. The expected value must be based on a quantitative representation of the Commander’s Intelligence Requirements (CIRs).

This research defines the practical MultiINT collection options against maritime targets and identifies the feasible methods to quantify an objective value function and orchestrate such a wide range of sensing systems against dynamic and fleeting maritime targets. The Naval Information Warfare Center (NIWC) Pacific’s (N66001-20-R-3412) solicitation for the development, technical, management, and engineering services for ISR systems and information operations from the Seabed-to-Space project highlights the importance of this research. NIWC is leading the development of ISR and information operations systems that operate with manned and unmanned platforms, including tactical data communications platforms, satellite terminals, autonomous systems or nonautonomous platforms for air, land, sea, and space missions. This research will support the NIWC efforts.

The research directly supports the focus of the Chief of Naval Operations (CNO) Navigation Plan issued January 2021 which focuses on the following elements:
1. “Emerging technologies have expanded the modern fight at sea into all domains and made contested spaces more lethal,” which is enabled by the resilient command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting capabilities, all-domain coordinated efforts, and project synchronized lethal and non-lethal effects across all domains.
2. “Ubiquitous and persistent sensors, advanced battle networks, and weapons of increasing range and speed have driven us to a more dispersed type of fight” because of the persistent sensors and information, Naval Operational Architecture that integrates with Joint All-Domain Command and Control, and a resilient web of persistent sensors, command and control nodes, platforms, and weapons
3. “Advances in artificial intelligence and machine learning (AI/ML) have increased the importance of achieving decision superiority in combat,” enabled by the ability to close the kill chain faster than our rivals and project synchronized lethal and non-lethal effects across all domains. (CNO, 2021, p. 4–5)

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

Findings and Conclusions
This evaluation focused on the most critical requirements for the satellite network use to accomplish the most stressful long-range cooperative engagement case. We established a set of critical “Admiral’s Questions” that will be posed to any briefer presenting the consideration of this complex operation:

- Can the Satellite Constellation provide required performance in three areas: 1) Relay latency to deliver sensor data in time? 2) Availability at critical times of engagement? and 3) Sensing revisit rates to support persistent detection, identification, tracking, and engagement?
- What would a realistic, stressful scenario look like? The surface warfare scenario looks very complex. Is it feasible? What is the next research step to assure feasibility?
- Can the dynamic network sustain ISRT start-to-finish? What are the operating parameters? What are the marginal areas? How do we increase the margins?

The results of this study have shown, at the depth of analysis performed:
- Conceptual coordination of Seabed-to-Space sensors via the planned DOD LEO space constellation relay is feasible and will enable DMO over-the-horizon operations for the stressful surface warfare scenario.
- Orchestration of the diverse sensors from seabed tip-off to space sensing and unmanned aerial system-unmanned aerial vehicle (UAV) support to perform coordinated fires is complex but feasible when space relay constellations demonstrate high availability.
- A constellation like the planned DOD Space Development Agency constellation as modelled, or larger, will provide coverage to enable distributed search, detection, and tracking capabilities but may require local UAV and unmanned surface vehicle support for terminal engagement.
- The network transaction process is complex but feasible; redundancy exists in sensors and in the network.
- We can address the admiral’s questions with supporting first-order data.
- The next required step is the simulation of scenarios like the scenario in this study over a range of conditions to measure statistical performance.

We found that the complexity of space-based sensing and relay is high, but feasible as demonstrated by our study— and the payoff for the Navy is high. During this study Rear Adm. James Aiken supported this very concept when describing a recent Navy experiment: “We teamed manned and unmanned vessels together. We also used the fusing capability … It was totally passive where we didn’t have active sensors on target… *We also look for space as well to actually identify the target* and then once we found the target, we were able to track it because of the [electromagnetic signal] its coming off the target, develop lines of bearing, then launched the missile” (Lagrone, 2021).
**Recommendations for Further Research**

While this study has used modeling tools to evaluate the concept of space-based sensing and relay to support distributed maritime operations, the next level of research will require quantitative modeling over a wide range of scenarios and network parameters (esp. latency, availability) to assess the statistical performance. The network transactions in the scenario studied exceeded 200 over a 24-hour period and even more complex scenarios must be evaluated. An example next-step study with greater fidelity could do the following:

- Utilize the Naval Surface Warfare Center Mast Simulation tool (or similar) to create stressful distributed maritime operations scenarios that include multiple dynamic maritime targets with radio frequency, electro-optical and radar signatures
- Use the Mast scenarios to drive a sensor and network model with transmission control protocol/internet protocol level fidelity to simulate the detection of maritime targets, relay of detection data, and control of sensors on the net.
- Include a fusion model to simulate the fusion and battle management functions to enable long-range engagement.

The next step will move forward the demonstration of the mechanisms necessary to achieve Adm. Aiken’s vision.

**References**


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**NPS-21-N091-A: Information Warfare in the High End Fight**

**Researchers:** Mr. Steven Iatrou, Mr. John Audia, Mr. Glenn Cook, and Dr. Douglas MacKinnon

**Student Participation:** Capt Molly Dundon USMC and Maj Benjamin Oydna USMC

**Project Summary**

This research is designed to help identify the gaps and redundancies in the way U.S. naval forces organize for, plan, and execute military operations involving both kinetic and non-kinetic forms of weapons systems. This research focuses on the convergence between the information and physical environments as it affects the ability to effectively employ non-kinetic and kinetic munitions.

U.S. naval forces are adept at coordinating kinetic fires and maneuvers and have developed proficiency in engaging opponents through the information environment (IE). However, there is a recognized deficiency in coordinating the kinetic aspects of engagements with the non-kinetic fires associated with information operations.
This research analyzes current doctrinal foundations of kinetic and non-kinetic operations in the context of literature focused on behavioral outcomes. Additionally, the research investigates the impact of the organizational design of the force structures on the ability to effectively coordinate cross-domain operations.

The doctrinal identification of an IE that is somehow separate from the traditional operational environment has created organizational, theoretical, and philosophical limits on the ability to effectively integrate kinetic and non-kinetic events focused on common objectives. The findings suggest that there is an over-reliance on kinetic options and associated operational elements at the expense of developing an understanding of non-kinetic options. This is, in part, due to conflicting and ill-defined terminology associated with non-kinetic options and further exacerbated by the establishment of distinct organizations whose responsibilities lie fully in each of these two domains.

**Keywords:** information operations, information warfare, non-kinetic weapons, non-kinetic targeting, military operations in the information environment, information environment operations

**Background**
Both state and non-state adversaries to the U.S. are capitalizing on the effects achieved from creatively incorporating physical assets and technological capabilities into larger strategic objectives involving operations in the IE. Tactics such as propaganda, psychological and deception operations reach beyond the physical impact of conventional munitions by exploiting the relationship between the data and information available to the individual and the perceived reality of the environment. The U.S. military has developed advanced capabilities in the deployment of physical weapons and informational weapons as separate means of compelling an enemy to do its will; the U.S. military has not, however, satisfactorily developed the capability to combine physical and information weapons to efficiently and effectively achieve this goal.

Modern targeting efficiency depends on weapon systems capable of integrating kinetic and non-kinetic payloads. Although non-kinetic munitions operate differently than kinetic munitions, their integration across the range of operations is becoming increasingly necessary. As near peer competitors to the U.S. aggressively pursue similar non-kinetic technological integration at a pace uninhibited by democratic procedures and requirements, American resources must address these new threats spanning the information and physical environments. While kinetic munitions will always be required for defense, non-kinetic munition integration can maximize their effectiveness or mitigate their use (allowing for greater physical capability sustainment during combat).

This research attempts to identify possible impedances preventing non-kinetic and kinetic munition integration across the range of military operations and proposes increased means for alleviating the friction incurred by those circumstances. This research focuses on the information and physical environments as well as the organizational issues that may impede efficiencies.

The data for analysis were developed through an extensive literature review of current doctrine associated with organization design, lines of authority, and command and control (C2) of forces; case studies of organizational impacts on information dissemination in the battlespace and in public perceptions; and biases that affect the interpretation of information and the subsequent individual actions based on these
interpretations. Two levels of analysis were studied. Information as it impacts individual decision making was explored as a means of understanding employment of information munitions against enemy targets, and decision making at the organizational level was explored to better understand how these non-kinetic tactics can be better integrated with well-established kinetic operations.

Findings and Conclusions
This research explored the phenomenon of U.S. naval forces’ ability to maintain expertise in the employment of both kinetic and non-kinetic fires yet demonstrate an inability to effectively blend the two disciplines into a cohesive operational construct. This study indicates that a major contributor to this lack of cohesion lies in the doctrinally established warfighting domains. The introduction of information as a new and separate warfighting domain (Joint Chiefs of Staff, 2017) creates a need for expertise in a subject that is a non-tangible, abstract psychological construct that traverses the physical and cognitive dimensions (United States Marine Corps, 2018.) Operations in the IE require extensive study in psychology and sociology and introduce concepts and language that are not well understood in the context of kinetic military operations. The gaps that have been created may be bridged by incorporating existing organizational concepts that are used to allow unique effective C2 of unique components of the overall operational command structure. The proven concepts of the supporting arms coordination center for integrating fires from multiple, dispersed elements (Meade, 2015) and the integration of submarines into fleet operations (Csutoros, 2017) may provide insight into how to coordinate fires across unique elements of the battlespace.

Recommendations for Further Research
Wargames, models and simulation, and table-top exercises should be developed to explore the existing command and control concepts associated with supporting arms coordination centers and submarine tasking as they might apply to the integration of kinetic and non-kinetic fires. Using a design-thinking approach to develop the command structures needed to integrate these two types of fires would allow experts from the kinetic and non-kinetic disciplines to develop an efficient and effective organization to meet operational objectives.

References

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NPS-21-N118-A: Effects of Cold Spray Repairs on the Mechanical Properties of a Component

Researchers: Dr. Andy Nieto and Dr. Troy Ansell
Student Participation: Maj Adrian Chua RSAF FORNATL

Project Summary
Cold dynamic gas spray, better known as cold spray, has generated much interest for repairing metallic components and depositing protective metal coatings. Naval shipyards recognize the potential of this technology to provide rapid repair and manufacturing capability and to replace welding as the state-of-the-art for metal joining and repairs. As cold spray evolves into a mature technology, there is a need to understand the mechanical behavior of widely used engineering alloys such as the cupronickel alloys. This study investigates the mechanical behavior of Cu-38Ni coatings cold sprayed onto Cu-10Ni substrates with and without an annealing heat treatment. The cold sprayed coated specimens undergo uniaxial tensile tests to study the durability of the cold sprayed coating layer and its effects on the overall mechanical behavior of the coated substrate. Annealing at 650 °C is found to enhance both the ductility and strength of the coating material. The annealed coating specimen experiences an elongation to failure of ~13.7%, while the as-sprayed specimen only experienced ~3.9% elongation. Adhesion tests show that annealing leads to a large increase in adhesion strength of the coating to the substrate due to solid state diffusion across the interface during the heat treatment. Annealing further leads to a reduction in pores, inter-splat cracks and porosity, and a more ductile and tough material due to recrystallized grains. Nanoindentation reveals that the cold as-sprayed material is the hardest, but also the most brittle, exhibiting plasticity of only 81%, as compared to 89-90% for the annealed coating and the substrates.

Keywords: cold spray, mechanical properties, heat treatment

Background
The Navy is interested in developing and implementing technologies that can be used for repair and protection operations at the site of need, such as naval shipyards or ships at sea. Cold spray is an emerging technology utilizing relatively low temperatures (compared to welding and other conventional metal working techniques) to deposit metallic deposits or coatings. The process requires a metallic feedstock (e.g., metallic powder particulates) and a high-pressure gas to accelerate the metallic particulates to supersonic speeds, which enables them to impact the surface with sufficient kinetic energy to adhere onto the material and form a continuous deposit, layer by layer. Such coatings can be used to provide protection from wear and corrosion. Similarly, cold sprayed deposits can be used in the same manner as conventional welds to repair and join metallic structures. Welded deposits often cause damage to the underlying metal. The relatively low temperatures used in cold spray allows temperature sensitive substrates (e.g., steel, magnesium, Cu-Ni alloys) to be sprayed without damage to the substrate. The cold sprayed deposits themselves exhibit excellent mechanical properties because of the strengthening imparted by the severe plastic deformation (i.e., work hardening) that the metallic powder particulates undergo during the deposition process.

However, what is still poorly understood is the nature of interfacial strength of the cold sprayed coating with the substrate and any possible effects (e.g., residual stresses, localized hardening) on the substrate
material. Furthermore, while cold sprayed deposits often possess good strength, without additional heat treatments, they may have insufficient or even poor ductility. If a substrate has sufficient ductility to undergo a graceful failure, it would be desirable for the coating not to fail at such a critical point. As such, the cold sprayed coating should have good ductility as well. The mechanical behavior of load bearing components with relatively thick cold sprayed deposits (300-700 µm) is still largely unexplored but critical to transitioning cold spray repairs onto the structural and load bearing arena. The objective of this study is to quantify the adhesion strength of cold sprayed Cu-Ni coatings on Cu-Ni substrates and investigate the effects of the cold sprayed deposits on the tensile strength and fatigue resistance of Cu-Ni.

This work investigated the mechanical behavior of Cu-38Ni coatings that were cold sprayed onto Cu-10Ni substrates and evaluated their mechanical behavior in the as-sprayed state, as well as after an annealing heat treatment. In this study the tensile mechanical behavior of a Cu-38Ni coating was evaluated, where the coating was about 9% of the substrate thickness. This type of test is more realistic to the actual application of cold spray, where a coating or cladding layer would be deposited on an existing substrate being repaired. Most studies to analyze the tensile strength of cold sprayed coatings have been on stand-alone coatings that are less likely to be representative of the actual conditions in which cold spray will be used.

**Findings and Conclusions**

Annealing was able to endow the coating with both enhanced ductility and strength. The heat treatment induced solid-state diffusion within the coating that reduced porosity and bridged intersplat cracks and pores, thereby enhancing strength. At the interface, diffusion between the substrate and coating was evident, and this led to a large increase in coating adhesion strength, from ~17 MPa to beyond ~46 MPa, the limit of the adhesive used. Annealing led to the expected increase in ductility, and evidence of finer recrystallized sub-grain structures within splats was observed via optical and scanning electron microscopy. Nanoindentation studies confirmed that the annealed coating experienced 89% plastic deformation (on par with substrate), in contrast to only 81% plastic for the as-sprayed coating. The elongation of the coating at failure increased by over a factor of three, from ~3.9% to ~13.7%. This enabled the annealed coating to survive well beyond the yield strength of the coated substrate. This is a critical benchmark for utilizing cold spray coatings in a structural application as it ensures the coating would be able to participate in load bearing and undergo plastic deformation prior to failing. In practice, most structural design is based on never reaching the yield strength and hence survival of the coating past the yield point of the substrate is critical.

These findings provide two critical pieces of information for the implementation of cold sprayed coatings for use in structural repairs: 1) cold sprayed Cu-Ni coatings can be robust enough to survive past the yield stress of a Cu-Ni substrate, and 2) heat treatments can be utilized to enhance adhesion, tensile strength, and ductility of cold sprayed coatings. Cu-Ni is widely used on shipboard components such as pipes and heat exchangers. These parts typically have minimal requirements for tensile yield strength. The current findings show that cold spray could be used to repair failed Cu-Ni parts without compromising the tensile strength properties of the substrate. In fact, a Cu-Ni coating could be sprayed with nitrogen, which is much cheaper than helium, and heat treated to ensure it will not fail prior to the yield point. The heat treatment process would be limited only by the size of the component to be repaired and the corresponding size of the furnace at the shipyard.
It is hence recommended that Cu-Ni parts repaired using cold spray be heat treated if the parts are load bearing or otherwise have minimal tensile strength requirements.

**Recommendations for Further Research**

Future studies may consider the use of helium as a carrier gas (nitrogen was used in this study). The use of helium could further improve the as-sprayed coating’s mechanical behavior as the coating particles would possess more energy to enhance metallurgical bonding. This might be a viable alternative to heat treatment, which constrains in-field applications due to the need to place the component in a controlled and enclosed furnace environment. Future studies should consider alternate spray parameters to achieve desired thick coating in one pass or resolve porosity between layers. Future studies should investigate other ways to enhance the adhesion, tensile strength, and ductility of cold sprayed Cu-Ni, such as by utilizing secondary reinforcements to yield a composite coating. Lastly, future studies are needed to investigate the fatigue performance of both the as-sprayed coating and the heat treated coatings.

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**NPS-21-N282-A: Operational Analysis and CONOPS Definition for Next Generation Mine Warfare**

**Researchers:** Dr. Paul Beery and Dr. Anthony Pollman Capt USMC Ret.  
**Student Participation:** LCDR Anthony Deken USN, Mr. Bradley Leusner CIV, Ms. Kaylee Zagrocki, CIV and Mr. Justin Lewis CIV

**Project Summary**

This project conducted operational effectiveness analysis to inform future operational concepts for mining. It defined candidate operational concepts for mining operations with a focus on capabilities and associated design requirements. It developed architectural representations of mining operations to highlight the operational activities and systems associated with mining operations and define the system design decisions (e.g., platforms and manning) that contribute to the operational effectiveness of minefield deployment. The project developed and analyzed an agent-based simulation model using the Modeling and Simulation Toolbox (MAST) feature of the Orchestrated Simulation through Modeling (OSM) framework developed by the Naval Surface Warfare Center, Dahlgren Division. The OSM MAST model was used to compare airborne, surface, and subsurface deployment strategies as well as the key performance drivers (in terms of operational activities, hostile behavior, and system design decisions) that drive operational effectiveness. Analysis demonstrated that hostile posture (defined in terms of enemy detection capability and probability to change course upon mine detection) had a larger impact on minefield effectiveness than any characteristics of the minefield, individual mine characteristics, or deployment vessel. Additional analysis was conducted on operational and design characteristics of deployed minefields which found that the quantity of the mines in the minefield had a larger impact than individual mine characteristics or deployment vessel. An isolated analysis of alternative deployment strategies found that, in general, airborne deployment vessels outperformed both surface and subsurface deployment strategies.
Keywords: offensive mining, agent-based simulation, operational effectiveness analysis, model-based systems engineering

Background
Naval mines are responsible for the sinking of more ships since World War II than any other weapon type. In a 1977 article in the United States Naval Institute (USNI) Proceedings, Rear Admiral Roy F. Hoffmann stressed the historical impact that mining operations have had throughout United States Navy conflicts, from the American Civil War through World Wars I and II to conflicts in both Korea and Vietnam (Hoffman, 1977). Rear Admiral Hoffman emphasizes that naval mining has historically played a prominent and effective role in warfare and creates an asymmetric advantage for the employer. In 2018, the same ideas were expanded, also in USNI Proceedings, by Admiral James Winnefeld and Captain Syed Ahmad (2018). In their article, they note that while U.S. naval mining capability has atrophied in recent years, there is immediate opportunity to expand the capabilities of the U.S. Navy through development and analysis of mining operations. Specifically, there are opportunities for advancement in mining operations that span communications, machine intelligence, command and control, detection, lethality, signature reduction, modularity, endurance, and reliability. Development of mining capability requires investigation of the systems responsible for the deployment, monitoring, and recovery of naval mines at the early stages of system development.

Recent efforts in mine warfare have resulted in increased interest and emphasis on surface and subsurface platform support for offensive mining. Previous studies and analyses have focused primarily on the employment of minefields and their resultant effects, with little regard to the impact of the mine delivery platform’s resultant unavailability to the joint operation. Accordingly, they have focused on isolated examination of minefield deployment and characteristics. This research expands previous efforts by examining alternative unmanned and manned systems of systems capable of deploying and supporting minefields as an integrated part of joint offensive operations. Specifically, it considers multiple candidate operating areas and alternative delivery platforms.

This project utilized quantitative analysis, supported by development of Lifecycle Modeling Language–compliant model-based systems engineering (MBSE) products and associated agent-based simulation models, to examine the scalability of minefield deployment and support. The modeling and analysis effort is summarized in Deken et al. (2021). The modeling effort was conducted in the Modeling and Simulation Toolbox (MAST) feature of the Orchestrated Simulation through Modeling (OSM) framework developed by the Naval Surface Warfare Center, Dahlgren Division. Use of OSM MAST enabled assessment of alternative delivery platforms (e.g., airborne vs. surface) using appropriate use cases for each platform. This analysis also assessed the impact that development of new classes of mines (e.g., smart mines) may have on the determination of appropriate delivery platforms. Student involvement focused on development of both the MBSE products and MAST models within OSM.

Findings and Conclusions
This project utilized an agent-based model in the OSM MAST framework to determine which operational and design decisions have the largest impact on the effectiveness of a minefield. For the analysis, the term offensive denial mining (ODM) was developed in lieu of traditional categories of offensive, protective, or defensive mining to minimize sensitivity and avoid potential classification issues resulting from
assessment of mining operations in specific geographies. The model simulated a friendly (blue) force deploying a minefield to disrupt the operations of a hostile (red) force. The model implemented a standard sequence of events where a blue delivery vehicle is generated and, based on the vehicle type and mine type the vehicle is employing, proceeds to either one or multiple deployment sites located approximately 50 nautical miles from the generation site. Upon deployment, the blue delivery vehicle exits the deployment zone, and red vessels in the area move to a destination point that may require transit through one of the minefields. Three classes of deployment vehicle were modeled: air, surface, and subsurface. Multiple design characteristics and operational employment decisions, such as the number of mines aboard each vessel, mine type, deployment time, and minefield geometry, were varied for each vessel. Additionally, red agent characteristics and operational decisions, such as mine detection capability, information sharing, and probability of fixing position or course change based on mine detection, were also varied within the MAST model.

ODM was defined and assessed in terms of two primary measures of effectiveness (MOE), termed delay and stop. The delay MOE was recorded as a binary variable where a score of one indicated that hostile agents adjusted course and zero indicated that no hostile agents changed course. The stop MOE was recorded as a binary variable where a score of one indicated that hostile agents abandoned their pre-defined missions and zero indicated that the hostile agents did not abandon their pre-defined missions.

Naval Postgraduate School Hamming High Performance Computing machines were used to conduct 27,740 runs of the MAST model. Findings were grouped into two categories. Broadly, the propensity of the hostile vessel to change course or fix position upon mine detection dominated the analysis. This indicates that shaping actions which may cause an enemy to operate boldly or to distrust that a minefield is present may have a larger impact on minefield effectiveness than any characteristics of the delivery vessels or of the minefield itself. In terms of minefield deployment and configuration, the total number of mines had a larger impact than any other design or operational employment decision. Notably, the increase in the number of mines had a larger impact when the minefield size was restricted to less than 20 mines, indicating that there may be diminishing returns for larger minefields. Note that the largest minefield modeled was 120 mines, and findings may change again at larger numbers. Finally, when comparing the overall effectiveness of the categories of blue vessels, airborne deployment outperformed both surface and subsurface deployment in terms of both the delay and stop MOE.

**Recommendations for Further Research**

This project developed an agent-based simulation of offensive denial mining (ODM) in the Modeling and Simulation Toolbox (MAST) feature of the Orchestrated Simulation through Modeling (OSM) framework. Future work is recommended to conduct more comprehensive examinations of ODM. Notably, more subjective aspects of minefield deployment are particularly interesting. As an example, the clandestine nature of subsurface deployment may not have been adequately emphasized within this study. An increased model duration or the presence of actively employed mine countermeasures operations by a hostile force may result in a preference for subsurface deployment when compared to either surface or airborne deployment, a finding that would be contrary to the results of this study. Additionally, there is substantial interest in the development and employment of sophisticated smart mines. The mines modeled in this analysis, while varied, were incapable of proposed behaviors such as communication, maneuver, and redeployment to create agile minefields. Depending on the speed of progress for materiel development of these smart mines, a follow-on study could easily implement any of these behaviors in
OSM MAST to assess operational impact. Finally, future work that implements alternative use cases and scenarios would be informative. The single-year timeframe of this study necessitated a number of simplifying assumptions in terms of mine deployment size, spacing, and geometry as well as in terms of geography, bathymetry, and weather. The OSM MAST model built in this study could be adapted and customized to implement changes in any of these areas to improve the generalizability of analysis findings.

References

NPS-21-N307-A: The Integration of Reliability, Availability, and Maintainability (RAM) into Model-Based Systems Engineering (MBSE)

**Researchers:** Dr. Bryan O’Halloran and Dr. Douglas Van Bossuyt  
**Student Participation:** LT Kyle Diatte USN

**Project Summary**
Model-based systems engineering (MBSE) methods have developed a strong foothold in the design space in industry. These methods have proven fruitful when the right method is applied to the right problem. Reliability, availability, and maintainability (RAM) is an equally important but different side of the same coin. Currently, there is a gap in applying a methodology to integrate the two in the design process, particularly when the design is complex. This work provides a methodology that results in the successful integration of RAM and MBSE that can be used during the early phases of design. The methodology was developed after an extensive literature review, followed by validation of the methodology through a use case where each step of the method is applied and explained.

**Keywords:** model-based systems engineering, MBSE, reliability engineering, reliability predictions

**Background**
Systems are becoming increasingly complex and so too must the design processes and methodologies that support them if they are to be successfully executed. Traditional paper-based processes of conducting systems design are antiquated and no longer able to take full advantage of the latest advantages, features, and functions of modern design processes and methodologies. As a result, MBSE methods are being increasingly relied on to develop and execute models that underlie many systems design processes to better facilitate complex system design.
Several known issues have arisen when attempts to integrate RAM and MBSE have been made in the conceptual design phase of a system. The first issue is that RAM is not fully integrated as a focal point of the design process, being relegated to an activity to get a “check in the box” and continue with the design process. The second issue arises around the timing when RAM is conducted—namely, the design team disagrees internally as to when it should be conducted. The inability to identify the point in time when RAM analysis should be conducted adversely impacts design, often leading to disastrous results. Reliability calculations may be conducted to provide a needed numerical value, but the calculations are not performed early in the design process, the effort and resources needed to realistically attain the needed value may cause significant delays or overruns in cost, with the worst-case scenario causing the dissolution of a project and its team. The potential undesired realization of this scenario creates the gap in RAM and MBSE integration that this work seeks to address.

To navigate design efforts and bridge the gap between RAM and MBSE integration efforts, a seven-step methodology is proposed to facilitate the integration of RAM and MBSE processes:

- Step 1: Define for the design effort the modeling language, structure, modeling process, and presentation framework.
- Step 2: Select an MBSE tool that can completely represent the system.
- Step 3: State system relationships/requirements.
- Step 4: Construct block definition diagram(s) (BDD) and consider additional diagrams and tool(s) as needed.
- Step 5: Define data requirements and gather data.
- Step 6: Make parametric diagrams.
- Step 7: Determine RAM values from parametric diagrams and compare to requirements.

This process is intended to provide a methodology to get from a design concept to a descriptive and logical system and subsystem states. Proper tool selection through an analysis of modeling language, structure, modeling process, and presentation framework will make it easier for the engineer to create the BDD and parametric diagrams while also showing the appropriate relationships and requirements. As stated in Step 4, the designer can use additional, more robust tools as needed to provide more detailed models and simulation results for analysis. The analysis as to the feasibility of the methodology was conducted through the application of a case study. This case study references real-world data with the methodology applied to show that the methodology presented is valid.

Findings and Conclusions
The results confirm that the methodology can be applied successfully to a real-world situation. A limitation was noticed that the methodology is best suited for designs where historical data is readily available. If historical data is not available, then assumptions must be made for certain values to determine results. If the diagrams in the early steps are made correctly, however, the process of following the methodology becomes easier as the design effort progresses.

The methodology presented provides a basic blueprint for effectively combining RAM and MBSE. Following the steps in order provides the optimal opportunity for saving time and reducing potential for rework, which lowers cost and scheduling overruns on the project. Beginning with Steps 1 and 2, the primary drivers in the MBSE realm are determined and selected based on the design needs. Stating the
system relationships in Step 3 shows how the different parts of the system interact. Step 4 is informed by the relationships and the effective creation of BDDs and other diagrams as needed. The incorporation of other tools to provide additional data or information should not be ignored despite the possible increase in time required to use the newly implemented tool effectively. If initial MBSE tool selection is limited in certain aspects, the incorporation of other tools and time to gain proficiency, if not achieved already, should be accounted for to provide the best long-term chance for success.

Defining data requirements, gathering the primary and secondary data, and ensuring data quality provide the foundation for getting the desired results needed for analysis. Making and evaluating the parametric diagrams and comparing them to requirements incorporates MBSE and RAM techniques, culminating in usable information for the engineer to decide on the design process. The comparison is critical for checking the processes of the design effort to determine if a single or multiple steps need to be readdressed to the desired degree.

There are multiple benefits from applying this methodology to a design effort. First and foremost, a clear way to navigate the integration of RAM and MBSE techniques is laid out. This results in savings of time and cost on the backend through getting RAM information earlier in the design process, thus informing changes to the design earlier in the process. Another benefit is the expansion of knowledge in this field of integration. The methods for joining RAM and MBSE techniques more effectively is incredibly valuable to the cost and schedule minimization. The topic sponsor will input the findings by checking their own process against the methodology developed. If there is an area where incorporating the methodology will improve their own processes, they will make the necessary changes to gain the maximum benefits.

**Recommendations for Further Research**
The priority for future work should be to determine the changes necessary to better suit this methodology to new design efforts for which minimal or no data is available. This would provide two different methodologies, each with its own set of characteristics and uses. The application of this methodology to a new design would be the best way to determine its feasibility.

There are four further areas of interest for future work:
1. Determining a methodology for using multiple tools at once and seamlessly transitioning between those selected.
2. Determining the effectiveness of this method using a different tool or modeling language.
3. Determining the feasibility of this method when incorporating multiple system models across various languages and tools.
4. What changes should be made to make the method presented better suited for wider application and distribution.

These areas for future research would expand upon the current work done in a meaningful way. This methodology would be tested in various conditions not touched on in the current work which would provide further refinement to the methodology presented.

Researchers: Dr. Bonnie Johnson, CAPT Scot Miller USN Ret., Mr. John Green, Mr. Walter Kendall, and Mr. Arkady Godin

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Project Summary
Advances in computational technologies and artificial intelligence (AI) methods present new opportunities for developing automated tactical decision aids to support warfighters making weapons engagement decisions. Tactical decisions become increasingly complex and can overwhelm human decision-making as threats increase in number, speed, diversity, and lethality. The deployment of such AI-enabled decision aids must consider system safety. This study explored the potential safety risks and failure modes that may arise as automation and AI technologies are introduced and implemented to support human-machine weapons engagement decisions. The study identified and evaluated safety risks and failure modes, root causes, and mitigation and engineering strategies to prevent, address, and recover from this new class of possible safety failures.

The study included five research initiatives. Dr. Bonnie Johnson conducted the first initiative to study the problem holistically and develop a taxonomy of safety risks, possible root causes, and mitigation strategies related to the introduction of AI into tactical decision aids. Naval Postgraduate School (NPS) students carried out the other four initiatives: (1) analysis of the decision risk involved in human-machine teaming for making weapons engagement decisions, (2) analysis of human-machine trust and weapons engagement decisions, (3) evaluation of the safety risks in implementing automated decision aids for air and missile defense, and (4) a study of data gathering and management, a critical enabler for AI safety, to support the Navy’s development of AI systems.

This study found that developing and implementing AI systems for military applications, especially for applications involving weapon engagement decisions, introduces new and potentially dangerous safety risks that must be taken seriously. The root causes of these failure modes may be difficult to detect, predict, and prevent. The study recommends continued research on the five focus areas and into systems engineering methods needed to ensure AI systems are designed, developed, implemented, and operated safely.

Keywords: safety, artificial intelligence, machine learning, human-machine teaming, automated decision aids, weapons engagements, mission planning, metacognition, trust, risk, missile defense, failures, root causes, systems engineering, tactical warfare

Background
The development of AI capabilities has the potential to transform the traditional battlespace. AI-enabled applications, such as automated decision aids for tactical missions (Johnson, 2019) and predictive
analytics and game theory for mission planning (Johnson, 2020; Zhao & Nagy, 2020), offer huge gains in naval decision effectiveness and tactical superiority. The speed of warfare today often exceeds the cognitive abilities of humans to make decisions (Galdorisi, 2019). The Navy has acknowledged the need for AI and machine learning (ML) to support warfighters. Naval warfighters need real-time decision aids to support mission planning and battle decision aids.

There is extensive research into data analytics, data fusion, AI, and ML; and automation taxonomies exist (Save, Feuerberg, & Avia, 2012). In parallel with the development of AI methods, studies are being conducted to understand the risks associated with AI capabilities and develop methods to ensure safety. Broad studies of the safety implications of AI systems are developing theories for achieving safe, intelligent systems (Kose & Vasant, 2017). Studies are developing taxonomies for the various pathways to dangerous AI (Yampolskiy, 2016). One concern is that adversaries may insert carefully crafted training sets with false information into ML models causing the ML systems to learn incorrectly (Chen et al., 2018). Some research is taking an opposing approach by taking the adversarial perspective and starting with the objective of how to create a malevolent AI system (Pistono & Yampolskiy, 2016). They hope to gain a deeper understanding of AI safety through this counter approach.

This study explored AI safety with a focus on the future application of AI methods for military applications. The study identified AI safety risks and developed high-level risk mitigation strategies. The study developed a framework for analyzing and engineering safety aspects of future AI systems for tactical decision aids and mission planning aids.

This study applied a systems analysis approach to understand the problem space and to develop engineered solution concepts. The study collected data and information through a literature review, participation in virtual conferences and workshops, and through discussions with subject matter experts. The study developed safety requirements for integrating automated decision aids into weapons engagement and mission planning decisions. The study explored the cognitive strengths of humans and machines to identify effective teaming arrangements in a variety of tactical and mission planning environments of increasing complexity. The study developed a set of complex threat scenarios to understand and evaluate human-machine weapons engagement teaming strategies. The study developed solution strategies throughout the systems engineering lifecycle of AI systems that need to be implemented to prevent, predict, mitigate, and recover from safety failures. The study involved a research team of faculty members at NPS and systems engineering student researchers. One thesis student and three capstone student teams contributed to the project.

Findings and Conclusions
The primary outcome of this study is the recognition that developing and implementing AI systems for military applications, especially for applications involving weapon engagement decisions, introduces new and potentially dangerous types of safety risks that must be taken seriously. The root causes of these failure modes may be difficult to detect, difficult to predict, and difficult to prevent.

This study discovered three fundamental reasons that the implementation of AI systems in the tactical military domain will lead to serious safety concerns.
The first is the nature of AI systems: they are non-deterministic, complex, and adaptive. AI systems learn while being trained and adapt to their operational environments as they receive data. AI systems often lead to emergent behavior and behavior that can be unexpected and unintended. As AI systems function and adapt to complex situations, they often contribute to the complexity. Future AI systems may even continue to learn in situ. For military applications involving weapon engagement decisions, it is critical to ensure that AI systems produce safe results.

A second reason is the role of data in the development and operation of AI systems. Developing AI systems requires a major effort in data gathering and management. Data must be representative of the operational scenario. Data is required to train, evaluate, validate, and operate AI systems. Data must be securely protected and evaluated, so it is free of bias and corruption.

The third factor is human-machine teaming. Human-machine teaming is a critical aspect of implementing AI systems effectively and safely. Appropriate trust must be established between human operators and AI systems. The appropriate level of automation (how automated or manual each decision needs to be) depends on how much decision risk is acceptable, and this depends on the complexity of the threat situation. For tactical decisions involving the use of weapons, the level of automation needs to adapt to the situation—if time is available, human operators will have time to weigh options; however, if time is very short, it may be necessary for engagement decisions to be made in a more automated mode to provide an effective defense.

These causal factors were studied by the NPS researchers and student teams using literature review, systems analysis, risk analysis, and through the study of operational use case analysis. The researchers identified a variety of tactical scenarios in which a future AI system could support situational awareness and tactical decision-making. The analyses revealed areas of safety failure modes, possible consequences, and potential root causes. The research led to the identification of system solution concepts for preventing, mitigating, or recovering from AI system failures. There are four categories of safety mitigation solution strategies that involve engineered capabilities as well as activities that must be performed during operations. Thus, the entire systems engineering lifecycle is affected. The research also led to the identification of systems engineering and program management practices that need to be implemented to support these AI system safety solution concepts.

**Recommendations for Further Research**

This study recommends continued research in five focus areas: artificial intelligence (AI) system safety solution concepts, AI system applications for the weapon engagement kill chain, human-machine teaming for this application, risk management, and data management.

The first focus area that requires continued research is AI system safety solution concepts. This study identified four categories of solution strategies that span the systems engineering lifecycle: inherently safe designs, building in safety reserves, developing mechanisms to allow for safe fails, and implementing procedural safeguards during operations. Each of these types of safety solution strategies needs to be carefully studied for any application that will be enabled by AI system capabilities. Additionally, these solution strategies must be tailored to the specific application domain.
The second focus area for future research is on the design and development of specific AI methods for implementation in future tactical kill chains. Initial findings from this study show that different AI methods will be needed for the different functions in the kill chain, and a more complex mapping will be required rather than a simple one-to-one mapping. It is likely that a federated learning approach will be required that orchestrates a heterogeneous set of machine learning algorithms and AI methods that can handle the highly complex spatial-temporal dynamics of a tactical battle scenario. A significant level of research is required to identify and evaluate different and novel AI algorithms and methods for this application.

The third future research area is human-machine teaming. This study focused on the trust relationship between human operators and future AI-enabled tactical decision aids and risk levels associated with different levels of automation. Similar research is required to study many other aspects of human-machine teaming including: explainability, useability, human factors, human-machine interdependency, cognitive loading, and adaptive and agile levels of autonomy.

A fourth area of future research is risk management. This study identified a set of operational use cases representing the use of future AI-enabled decision aids for air and missile defense missions. The study conducted a risk analysis to identify and analyze potential failures, consequences and root causes. Additional risk analysis is required for these threat scenarios as well as for many other mission domains. Risk analysis needs to be performed continuously during the systems engineering lifecycle of the design, development, and implementation of future AI systems for military applications—especially for weapon engagement decisions.

A fifth area that requires future research is data management in support of AI development. This study revealed the importance of data management for effective AI system design, training, evaluation, and operations. Additionally, the study found that acquiring, curating, formatting, validating, and using data in support of AI system development is a major undertaking and systems engineering task in its own right. It is crucial that the Navy recognizes the importance of appropriate data acquisition and management to support AI development and ensures that funding, acquisition, and program management supports it—for weapons engagement applications and other mission domains.

References


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**Researchers:** CAPT Scot Miller USN Ret. and Dr. Mollie McGuire  
**Student Participation:** Capt Andrew Benton USMC

**Project Summary**

The MQ-25A is an unmanned carrier-based aircraft designed to provide air-to-air refueling to the carrier air wing and, as a secondary mission, provide intelligence, surveillance, and reconnaissance (ISR) support. Initial operational capability (IOC) is scheduled for 2024. Current carrier air wing refueling is supported by organic, manned aircraft. This limits the number of strike mission sorties and burdens the air wing with a plethora of secondary missions. This research examined the human-machine teaming aspects of MQ-25A operations during air-to-air refueling and ISR missions only. Launch, recovery, and flight deck operations were not included.

To explore human-machine teaming between this new unmanned tanker and the air vehicle operator (AVO), this research employed interdependence analysis (IA), which is a systems engineering design technique that identifies interactions required between humans and machines to successfully complete a shared mission. This interaction between humans and machines occurs in three general areas: observability, predictability, and directability. IA assists analysts in defining all functional paths through a mission, which promotes reliability. IA also supplies a thorough “what if” audit, which identifies methods to increase system resiliency.

Two findings emerged: First, the MQ-25A operates in a permissive environment; that is, communications links and the global positioning system are expected to be operating during MQ-25A flights. This represents a significant assumption, as the Navy admits near-peer operations will occur in a denied, disrupted, intermittent, and limited (low-bandwidth) communications environment.
Second, the upgraded precision landing mode (PLM) makes the nightmare known as night carrier recovery less hazardous and more reliable.

Recommendations are twofold: Explore potential human-machine teaming required in a nonpermissive communications environment; second, investigate the human-machine teaming needed for more advanced ISR capabilities embedded on the MQ-25A.

**Keywords:** MQ-25A; intelligence, surveillance, and reconnaissance; ISR; air vehicle operator; AVO; global positioning system; GPS; precision landing mode; PLM; air-to-air refueling; (non) permissive environment; unmanned; human-machine teaming; interdependence analysis

**Background**

The MQ-25A is an unmanned, carrier-based aircraft designed to provide air-to-air refueling to the carrier air wing and, as a secondary mission, provide ISR support. IOC is scheduled for 2024. Current carrier air wing refueling is supported by organic, manned aircraft. This limits the number of strike mission sorties and burdens the air wing with a plethora of secondary missions. This research examined the human-machine teaming aspects of MQ-25A operations during air-to-air refueling and ISR missions only. Launch, recovery, and flight deck operations were not included. The topic sponsor is the engineering development lead for the MQ-25A program office.

With an IOC of 2024, the program office has an approach to provide a robust and capable platform to support the mission. Indeed, the first squadron is receiving assigned sailors now. This research, by providing a second set of eyes, was designed to identify any unidentified surprises. Defining human-machine teaming requirements, as described in the Co-Active Design process (Johnson, 2014), provides a rigorous approach to identifying the capacities required for humans and machines to complete the air-to-air refueling and ISR missions. The Co-Active Design approach has been used on more than a dozen prior NPS theses, exploring various manned and unmanned teaming situations. Consistently, the process has delivered keen insights and prioritized requirements.

The research approach was straightforward: learn as much as possible about air-to-air refueling, the new MQ-25A, ISR, and also standard carrier operations. This approach included using the Navy’s Naval Aviation Training and Operating Procedures Standardization manuals, known as NATOPS.

An element of Co-Active Design is IA, which is a systems engineering design technique that identifies interactions required between human and machines to successfully complete a shared mission. IA begins by capturing the specific capacities of the mission, which may be performed by either unmanned machine or human. The IA approach asks the analyst, “How good is the machine at performing the capacity, and how can the human assist?” and vice versa. This interaction between humans and machines occurs in three general areas: observability, predictability, and directability (OPD). The analyst then suggests how the OPD might be executed for this specific capacity. IA also assists analysts in defining all functional paths through a mission to understand system reliability. IA provides a thorough “what if” audit, which identifies possible methods to increase system mission resiliency.
The initial research hypothesis was that the MQ-25A would be operated in a nearly teleoperated mode and would be ripe for capacity automation recommendations.

**Findings and Conclusions**

The program office performed stellar engineering preparations. The MQ-25A is not teleoperated per se, just designed with a magnificent autopilot so that the AVO operates it by establishing altitudes, waypoints, and orbits. The emergence of the PLM (Eckstein, 2021) on F/A-18s makes their recovery rate high. In the past, there was a nightly occurrence of a jet running on fumes, waiting to tank. Such emergencies are rare now. This means that perilous night tanking operations, with new AVOs, do not appear likely.

The approach to fleet introduction is also interesting. While it appears the MQ-25A will perform well, there is no intent on the first couple of deployments to dismiss manned refueling operations. Carrier air wings will slowly grow the capability, first trying daytime air-to-air refueling with the MQ-25A, then eventually moving to nighttime air-to-air refueling. Mission critical tanking operations will remain the province of manned tankers to begin with. This aligns well with other human-machine teaming trust development techniques (Yurkovich, 2020).

Because the program office desired this research to serve as an outside look, researchers had little access to many program office events that would have provided deeper understanding of the MQ-25A. For instance, the first refueling of an F/A-18 by the MQ-25A occurred in June 2021 (NAVAIR, 2021), but researchers were not invited to the event or privy to the results.

In the near term, research found that the Navy has a competent airframe, a well-organized rollout, a training program for the AVOs, and perhaps most importantly, the Navy decided to attach the MQ-25A carrier detachment personnel to the E-2D squadron to provide guidance, insight, comradery, and professionalism. The AVOs are planned to be Warrant Officer Grade One, to start, with a high school education. Giving them a home aboard ship will help build confidence, instill team spirit, and produce an understanding of the importance of the tanking mission, for both strike missions and recovery operations.

MQ-25A will begin carrier life with modest ISR equipment, including a low-end electro optic/infrared sensor, a mid-grade electronic support measures system, and an automatic identification system, the merchant ship equivalent to an airborne transponder. These passive systems make the MQ-25A, as an ISR platform, dependent on others’ transmissions.

While the MQ-25A development is proceeding, two obvious recommendations emerged. First, the program office should research human-machine teaming requirements for operating the MQ-25A in a non-permissive environment, meaning little-to-no communications and positioning equipment are available. Aircraft carriers, for tactical purposes, often operate in emission control conditions, where radios are seldom used. It would be difficult to see the Navy deploying an unmanned system and then not using it much of the time. Second, so far, it appears that ISR capabilities are an afterthought. There are many possible improvements that could make the MQ-25A an ISR force multiplier, but that also requires defining the human-machine teaming needs to implement better sensors and processing capabilities.
Recommendations for Further Research

The MQ-25A is an unmanned carrier-based aircraft designed to provide air-to-air refueling to the carrier air wing and, as a secondary mission, provide intelligence, surveillance, and reconnaissance (ISR) support. Initial operational capability is scheduled for 2024. Current carrier air wing refueling is supported by organic, manned aircraft. This limits the number of strike mission sorties and burdens the air wing with a plethora of secondary missions. This research examined the human-machine teaming aspects of MQ-25A operations during air-to-air refueling and ISR missions only. Launch, recovery, and flight deck operations were not included.

While the MQ-25A progresses apace, this is the first of its kind, so there will be a significant amount of learning and updates required. Several are emerging based on this research.

First, research is needed on the entire mission planning realm associated with the MQ-25A. If it is just a written plan for the air vehicle operator to follow, that might be fine for simple ISR and refueling missions. More complex operations, though, will need formal digital plans. The Navy already has the Joint Mission Planning System and is planning a next generation planning system for the E-2Ds and the F/A-18s. Should the MQ-25A be a part of this planning software? In the longer term, one might assume that other aircraft might take control responsibilities for the MQ-25A, and improved interoperability is more likely if all carrier air wing aircraft use the same planning software. This would help make system development to meet the observability, predictability, and directability requirements easier to design and manage. Similarly, all carrier air wing aircraft ought to have a common digital debriefing system as well. Emerging artificial intelligence techniques and systems, perhaps installed on the MQ-25A, could leverage these historical data to discern enemy intent.

Second, this author completed two cruises on an aircraft carrier, and other than carrier qualifications, strong effort was made to reduce or eliminate any radiated emissions. However, the MQ-25A right now is only required to operate in a permissive navigation and communication environment. This does not align with all the other air wing aircraft, which routinely operate in emission-controlled environments. The reason is obvious. Operating an unmanned aircraft in such an environment is hard. Future research should investigate the need to create interdependence in such an environment.

Current research explored reliability and resilience factors of the MQ-25A, and they were found to be well considered. However, in a nonpermissive environment, these factors will be much different, and therefore deserve another look.
NPS-21-N387-A: Weapon Systems Safety When Deploying AI Technology

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Student Participation: CDR Edgar Jatho USN, LT Sabrina Atchley USN, LCDR Brandon Beckler USN, Capt Sean Gilroy USMC, LT Cardavian Lowery USN, Capt Benjamin Marsh USMC, Capt Shane Wescott USMC, and Mr. Eugene Williams CIV

Project Summary
We investigated how artificial intelligence (AI) technology that impacts system safety concerns should be developed. Guidance is needed for understanding the likelihood of unwanted events and making risk decisions on naval employment of systems that incorporate such technology. The project identified hazards associated with AI systems, analyzed differences between hazard analysis of such systems and those for explicit programmed systems, and explored possible mitigations for those hazards. We found that the current state of knowledge in the area does not yet provide effective mitigations for several of these hazards.

Keywords: system safety ordnance, artificial intelligence, AI, Naval Ordnance Safety and Security Activity, NOSSA, development processes, safety analysis

Background
Safety concerns arise when deploying AI technology in weapon systems, autonomous systems carrying weapons/sensors/comms, and mission planning and decision aids. When AI technology is deployed in a weapon system, robot, or planning system, there is a likelihood that unwanted events occur. Naval Ordnance Safety and Security Activity (NOSSA) is responsible for understanding that likelihood and making risk decisions on naval employment.

Existing standards and guidance for assessing software system safety are geared towards explicitly programmed systems. These standards need to be augmented and extended to address systems that use machine learning to teach a computer to learn concepts using data without being explicitly designed and programmed.
Safety aspects of AI are complex and involve a wide range of concerns beyond the correctness of the algorithms used in deployed systems and in the tools used to train the models embedded in the AI. These models support decisions and recommendations made by AI subsystems, and the quality of the decisions and recommendations depends on how well those models match the real world, not just how well they match a finite set of available data. Relevant concerns include adequacy of the training data; validity of the training objectives; understanding implicit requirements derived from data; situational awareness for people teaming with the AI components; procedures for recognizing and recovering from failures; how AI system behavior interacts with doctrines, procedures and constraints of the larger systems and organizations in which the AI applications are embedded; and how well AI behavior can adapt when those doctrines, procedures, and constraints change.

Safety of AI systems is related to open fundamental issues in risk analysis. Almost all previous work on risk analysis defines risk as a function of (1) the probability of occurrence of an unwanted event and (2) the severity of the consequences should that event occur. The assumption that the probability of occurrence does not change with time is implicit in this definition and current risk analysis practices. This assumption does not match the context of Navy operations. For example, the probability of hostile action by adversaries is expected to be very different during active conflict and during peace time. We did not find formulations of risk analysis that account for this possibility.

The study was conducted by doing a literature search, analyzing previous publications in a research seminar with student and faculty participants, focused on previous work on identifying AI hazards and potential mitigations. Students explored case studies focused on effectiveness of possible mitigations. A PhD dissertation was initiated to further study problems related to this project.

Findings and Conclusions

We found that a major cause of accidents involving systems with embedded automatic control systems such as autopilots for airplanes and cars was lack of situational awareness when the systems recognized conditions they could not handle and handed control back to a human “safety driver” (Kroll & Berzins, 2021). We did not expect this finding, but after it was brought to our attention, students found Navy examples and identified a further implication: the skills and training of safety drivers tend to get rusty because they no longer get much practice in piloting their systems manually. Resulting recommendations included requiring safety drivers to do emergency recovery training while they were supervising autopilots operating under routine conditions, to focus that training on responding to a variety of failure conditions, and to add additional system design requirements for autopilots to provide “early warning” alerts when unusual conditions are detected. The early warnings could be used to cue the safety pilots to focus on the situation before it becomes a crisis and to bring the most experienced pilot available to the controls.

We believe this is a concern for the Navy because AI technology will not reach the state where it is sufficiently trustworthy for full autonomous control in the foreseeable future, at least for safety-critical applications such as weapons systems (Kroll & Berzins, 2022). This implies that man-machine teaming will be the expected mode of operation, and that these systems will have human “safety drivers” who will need mitigations for the hazard discussed above, such as additional training and additional design requirements for early warning of control handover.
Analysis indicates no defense in the literature currently stands as a viable answer to the problem of adversarial examples (Jatho et al., 2021). Adversarial examples are attacker-crafted inputs that reliably produce different outputs than developers of neural networks intended. Such networks take data as input, typically from sensors, and produce classifications as outputs, such as what kind of objects are present in an image. Adversarial examples is an active research area in AI. Fifty unique approaches to generating adversarial examples are represented in the Adversarial Robustness Toolbox alone (Nicolae et al., 2019), and new approaches are generated regularly. A recent paper states that “The field has not advanced to the point where we know how to build solid defenses even against the attacks that we know already exist” (Barton et al., 2021). The project studied new approaches to improve these defenses and developed an approach that improves performance over all previously known methods (Barton et al., 2021).

Our overall assessment is that the state of the art in safety assessment of systems with AI components is not sufficient for Navy needs and that further development in this area is needed.

**Recommendations for Further Research**

The project identified hazards associated with artificial intelligence (AI) systems, analyzed differences between hazard analysis of such systems and those for explicit programmed systems, and explored possible mitigations for those hazards. We found that the current state of knowledge in the area does not yet provide effective mitigations for several of these hazards. Further research is recommended to answer the questions below:

- How can AI systems provide early warnings when they encounter unusual conditions that are not well covered by their design or training data?
- How can the time-dependent nature of probability of hazard occurrence be incorporated into risk analysis?
- Can a game-theoretic approach to risk analysis be developed, and how would it apply to safety assessment with respect to contested environments?
- How should human safety operators responsible for overseeing AI systems be trained?
- How should doctrines, techniques, procedures and concepts of operations be reviewed and adjusted to ensure they do not pose safety hazards when interacting with AI systems?
- How to validate whether training data adequately covers possible real-world events that could impact operational safety?
- How to ensure that biases implicit in the way data sets are constructed do not degrade quality of decisions from AI components built using the data?
- How to assess risk exposure due to possible attacks on AI systems that use adversarial examples?
- How can risks due to adversarial examples be mitigated?
- How can risks due to faults in the optimization criteria used to derive AI decision rules from data be detected and mitigated?
References

NPS-21-N392-A: Commercial Batteries for Navy Use (Continuation)

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

Project Summary
This project sought to assist the Navy by identifying key battery industry trends and potential approaches for working with the industry. Recommendations from our previous report in fiscal year 2020 include enhanced collaboration among Navy organizations and suggested potential contracting mechanisms that might enhance the Navy’s effectiveness in working with the battery industry. During fiscal year 2021, we developed a cost model that could assist the Navy in developing and evaluating alternative courses of action with respect to ensuring security of supply for batteries. We developed a spreadsheet using Excel and the Crystal Ball plug-in, which asks the user to input a desired procurement scenario and cost factors. The model then generates the total cost and projected inventory levels for each scenario.

Keywords: batteries, cost model, acquisition, industrial base

Background
Information sharing and an increase in market knowledge about suppliers leads to more informed contracting decisions, which result in better outcomes. These contracting decisions are tightly interrelated with engineering, logistics, maintenance, and financial considerations. Development of sound acquisition strategies should be informed by an understanding of the cost implications of different courses of action, as well as the inherent risk of stockout due to uncertainty of both demand and supply.

We developed a cost model that could assist the Navy in developing and evaluating alternative courses of action with respect to ensuring security of supply for batteries. We developed a spreadsheet using Excel and the Crystal Ball plug-in, which asks the user to input a desired procurement scenario and cost factors. The model then generates the total cost and projected inventory levels for each scenario.
Findings and Conclusions
We found that military customers represent only a small part of the global demand for batteries. Therefore, a long-term approach by the Navy that goes beyond lowest-cost procurement based on short-term requirements would benefit domestic suppliers. However, any acquisition strategy needs to reflect the need for a certain degree of stability in the volumes of batteries purchased. Our cost model reflects the differences in abilities of industry to respond given specific demand scenarios. For example, investing in increased manufacturing capacity requires expenditures from current budgets but leads to improvements in the security of supply in subsequent years at a lower unit cost. In contrast, larger quantities of batteries can be purchased for immediate delivery on the spot market at a higher unit cost. However, doing so does not improve long-term production capacity, which can lead to stockouts in the event of a surge in demand.

Recommendations for Further Research
The Navy could possibly benefit from cost modeling of alternative courses of action for battery acquisition, whether for contractual procurement of specific quantities of batteries or investment in the industrial base. Cost modeling, when combined with projections of inventory levels in the event of a surge, could assist in supporting expansion of the domestic battery industry. The resulting improvement in security of supply would support a higher state of readiness, particularly given the possibility of surges in demand.

N1 - MANPOWER, PERSONNEL, TRAINING & EDUCATION

NPS-21-N298-A: Evaluating the Effectiveness of Blended Learning Strategies in Navy Training

Researchers: Dr. Simona Tick, Dr. Amela Sadagic, Dr. Kathryn Aten, Dr. Raluca Gera, and Ms. D'Marie Bartlof
Student Participation: LCDR David Aguilar USN and LT Ryan Wickham USN

Project Summary
The Ready Relevant Learning (RRL) initiative is transitioning the Navy to a modern, science-of-learning approach to deliver modernized, efficient, effective, and adaptable training to meet increasingly complex needs of the fleet (Chief of Naval Operations [CNO], 2019). To adequately address the development of personalized and adaptive training techniques required by RRL, Navy leaders require a better understanding of how blended learning environments, which leverage technology to incorporate greater personalization into distributed learning, generate value to the Navy and to Sailors. This study employs a user study framework to analyze the learning and experiential outcomes from implementing blended training strategies using existing Navy training classroom-based curriculum and learning materials in designed reconfigurations that mix web-based interactive content and in-class activities. Using tablets and a blend of learning strategies supported by an online platform that supports sharing, annotating, and creating content in a collaborative and persistent space, the analysis suggests that students and instructors’ experiences with blended learning strategies were positive and present opportunities for continued
implementation. Our study suggests that adopting a blended training environment approach—which combines learning strategies empowered by the modern technology solutions, web-based delivery, and traditional classroom methods—could offer a balanced solution to developing modernized, efficient, effective, and adaptable training delivery systems with integrated ability to assess training quality and impact on fleet readiness and on-the-job performance.

**Keywords:** blended learning strategies, Navy training, Ready Relevant Learning, RRL, instructional design

**Background**

This study’s evaluation of the effectiveness of blended learning strategies supports meeting the CNO-directed acceleration of RRL requirement outlined in both the CNO’s Design 2.0 and FRAGO 01/2019 documents related to the delivery of modern training content anytime and anywhere. Currently, the Navy’s approaches to instructional system design do not adequately address the development of personalized and adaptive training techniques integrated into the future learning continuum concepts required by RRL (CNO, 2019). Leveraging technology to incorporate greater personalization into distributed learning experiences could enhance learning effectiveness and skill acquisition in a blended training environment that combines online materials, modern technology solutions, and traditional classroom approaches. To adequately address the development of personalized and adaptive training techniques required by RRL, there is a need to evaluate the effectiveness of blended training.

This study analyzes the effectiveness of blended training environments using the existing classroom-based curriculum and learning materials from the Seabees Utility Technician “C” (UTC) School in designed reconfigurations that mix web-based interactive content, mobile technology, and in-class activities, coupled with an online student evaluation system.

The study aimed to address the following questions:

1. What are the outcomes of blended training in the UTC School course when compared with those from the current, training learning environment?
2. What are the pros and cons of resource use associated with using blended versus the traditional training methods?

To address these questions, this study uses a stepwise approach:

1. Determine learning data requirements and design a data collection capable of capturing measures of training outcomes.
2. Using existing learning materials, reconfigure content and learning strategies to use on a digital platform for distributed learning, coupled with use of mobile learning technology and an online student evaluation system.
3. Conduct a user study to collect data to test the effectiveness of the blended training versus traditional training methods for the “C” school course.
4. Analyze the training outcomes and resource use for the blended and traditional training methods.
5. Based on the analysis, formulate recommendations for the roadmap for development and implementation at scale of adaptable blended training.
Blended training can present challenges stemming from difficulties inherent in mobile learning technologies and distributed learning. Understanding the role of cognitive factors and processes and the adaptive behaviors and communication that impact learning outcomes and satisfaction can help assess the effectiveness of blended learning strategies. To assess the role of cognitive factors and behaviors on performance and satisfaction in traditional and blended learning environments, this study uses a data collection design drawing on the technology adoption model from Aten and DiRenzo (2014). The user study design uses observations, surveys, and interviews of students and instructors to collect data before and after participating in traditional and blended learning activities.

**Findings and Conclusions**

The data analysis suggests that initial experiences with blended learning strategies generated value to Sailors and instructors after overcoming technology and connectivity challenges, and these experiences present opportunities for continued implementation. Overall, the performance scores indicate that blended training strategies are as effective as traditional training, with the potential to be more effective. What is needed to maximize the potential of the training conducted in blended learning strategies is increased satisfaction with the learning environment. That could be achieved with pre-training of Sailors and instructors to fully leverage the mobile learning technologies and by insuring connectivity and interconnectivity with the existing training, assessment, and data repository infrastructure.

To scale the implementation of blended training environments, the Navy decision maker needs to account for command opportunities and limitations, both technical, such as providing connectivity for Sailor access to learning opportunities, but also administrative, such as communicating command expectations for when Sailors can engage in learning (during the work hours or on their own time).

**Recommendations for Further Research**

To scale the implementation of Navy blended training environments, future studies can test different models of blended learning that can maximize the benefits of synchronous and asynchronous learning (asynchronous before or after synchronous, asynchronous and synchronous at the same time, asynchronous with synchronous check-ins). Additionally, further research can explore the integration of experiential learning opportunities for vocational training while another study can consider addressing the connectivity and interoperability challenges that can grow when learners are at different commands.

**References**


NPS-21-N299-A: Mobile Learning Technology: Assessment and Recommendations

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**Student Participation**: MAJ Shawn Mosley USA, LT Russell Evans USN, LTJG Jennifer Kaylor USN, LT Mila Quan USN, LCDR Janson Lemma USN, and LCDR Samuel Mendoza USN

**Project Summary**

The Chief of Naval Operations (CNO) envisions an environment of continuous learning behaviors to broaden and deepen warfighting knowledge and allow the U.S. Navy to out-think and out-fight any adversary (CNO, 2019). To maintain a ready, relevant, and competitive force, the Navy must evolve and leverage mobile technologies in training. To do this, Navy leaders require a better understanding of how to offer mobile learning environments that create value for the Navy and its students (CNO, 2019). This study investigates under what conditions will implementing mobile learning technologies provide the most value, what are the requirements for delivering educational value to Navy users of mobile learning, and what are the pros and cons for Navy users of personal versus government-issued mobile learning devices. We conducted three phases of analysis: we investigated users’ perceptions of the costs and benefits of mobile technologies, identified accepted best practices of cyber management for mobile technology implementations, and conducted a value (cost benefit) analysis. Our analysis suggests that to implement mobile learning technologies, Navy leaders should incorporate the context of use into decision making, standardize and secure hardware and software, and institute a design system.

**Keywords**: mobile learning, technology, training, cybersecurity, internet, cloud based, technology adoption

**Background**

This study supports the Navy’s ability to meet requirements outlined in both the CNO’s Design 2.0 and FRAGO 01/2019 documents related to the delivery of modern training content anytime and anywhere and will support the Navy’s Ready, Relevant Learning (RRL) initiative. RRL is transitioning the Navy from outdated training delivery practices to the delivery of training content at the point of need. RRL requires a true anytime, anywhere capability for locations around the world and in the continental United States’ learning centers and schoolhouses.

While new technologies that can be leveraged to meet this end-state exist, the Navy needs to ensure that Sailors have access to mobile devices capable of supporting training practices and content that reside outside the schoolhouse; that those training resources are increasingly made available; and that they can be reached by means of the global and local computer networks, both wired and wireless. Sailors are currently not issued Wi-Fi–enabled mobile devices capable of loading and presenting the training content and practices via networked solutions. Information assurance policies prohibit commercial Wi-Fi on the Navy-owned and issued mobile devices (iPads, e-readers, smartphones). While the cybersecurity measures are created to protect computer infrastructure, they also act as a barrier to adopting new training and education applications. The Navy needs means and solutions that will provide learners with unimpeded access to mobile learning technologies.
This study identified and assessed options for providing sailors access to training content and practices—resident, online, or “in the cloud”—such that students could study and review those resources outside the classroom. The study addressed the following questions:

- Under what conditions will implementing mobile learning technologies provide the most value?
- What are the requirements for delivering educational value to Navy users of mobile learning?
- What are the pros and cons for Navy users of personal vs. government-issued mobile learning devices?

To answer the research questions, we conducted three phases of analysis: the research team investigated users’ perceptions of the costs and benefits of mobile technologies, identified accepted best practices of cyber management for mobile technology implementations, and conducted a value (cost benefit) analysis. The team conducted interviews with 19 users of Navy training and 11 Navy cyber personnel and then coded interview transcriptions. To investigate users’ perceptions, we drew on the technology acceptance model, which purports that technology use is predicted by “perceived usefulness” and “perceived ease of use,” which predict peoples’ attitude towards use, which in turn predicts behavioral intention and actual use (or not) (Alsharida et al., 2021; Buabeng-Andoh, 2018).

**Findings and Conclusions**

The analysis identified respondents’ perceptions of the costs and benefits of adopting mobile learning technologies and the factors that influence the likelihood that they will adopt.

Respondents indicated that productivity, career information management, and skill development influence their perceptions of usefulness. However, the importance of these factors was highly dependent on the context of use: ashore versus afloat and during active versus reserve duty. While existing research suggests that mobile learning technology self-efficacy influences perceptions of usefulness, this was critical to respondents in this study. The ability to readily understand the technology, the efficiency with which it helps them accomplish tasks, and their overall satisfaction influence their perceptions of how easy the technology is to use. Additionally, organizational factors that influence the likelihood of adoption include coordination of effort and developing a training culture.

- **RQ1:** Under what conditions will implementing mobile learning technologies provide the most value?
  Responses suggest that mobile learning technologies are likely to provide the most value when sailors can associate the training and technology with improved performance and promotion; perceived value is dependent on the perceived benefits of better performance and career advancement outweighing the costs of mobile technology use.

- **RQ2:** What are the technology requirements for delivering value to Navy users of mobile learning?
  Users’ responses suggest four critical requirements influence perceived ease-of-use: effectiveness, efficiency, learnability, and satisfaction. Respondents’ assessments of technology requirements vary depending on the context of use.

- **RQ3:** What are the pros and cons of bring your own device versus command-issued devices?
  Decisions regarding which mobile learning technology to use depend on the type of training, the work environment, and the accessibility of resources. Some respondents expressed the need to separate their personal life from work and thus have separate devices. Those who prefer to use their own...
devices want to maintain privacy and avoid responsibility for an extra item. For government-issued devices, respondents expressed the concern that users have shouldered the burden of accountability for lost or damaged government-issued equipment and lost productivity due to unavailable features or downtime for maintenance.

When selecting, designing and, implementing, mobile learning technologies, Navy designers should create an integrated design system to manage design across the enterprise and integrate key stakeholders into the development process. Design systems create standards and consistency across different modalities and are an emerging best practice in industry. The study provides a roadmap to guide the development of a design system, mobile learning technology guideline checklist, and summary of relevant policies.

Recommendations for Further Research
When the Navy identifies potential sites for mobile learning implementation, future research should use the tools developed in this study to assess specific alternatives in the context of use, prior to implementation.

References


NPS-21-N315-A: Assessing Inclusion Behaviors and Impact of Inclusion within the Fleet

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Student Participation: LT Pamela Goly USN, LT Frank Chavez USN, LT Keyaira Jackson USN, and LT Anthony Caballero USN

Project Summary
This project supports the Navy’s efforts to promote diversity and inclusion (D&I), which are recognized as strategic imperatives that give the Navy a warfighting advantage against our adversaries. The study utilizes both quantitative and qualitative approaches to understand the major contributing factors to an inclusive and diverse command, accomplishing four research objectives: (1) developing metrics to assess behaviors of inclusion within the fleet; (2) assessing inclusion behaviors within the fleet using the developed metrics; (3) determining the most impactful D&I competencies for building inclusion; and (4) identifying command practices that contribute to greater acceptance of diversity. We develop and
introduce a survey instrument to assess Personal Inclusion Factors (individuals’ feelings of being personally included within their command) and Command Core Inclusion Competencies (individuals’ beliefs about how their commands demonstrate diversity and inclusion) suitable for a Navy context. The instrument captures best practices and validated metrics for promoting and assessing D&I in organizations and tailors them to the Navy and Sailors’ work. We fielded this survey to 489 active-duty Navy personnel (enlisted and officers) asking them to report on both their current and past commands. We find that females across all race/ethnicities on average report lower feelings of inclusion and rate commands lower on Core Command Inclusion Competencies than their male counterparts. This gender difference is stronger for sea versus shore commands. Participants also answered open-ended questions about the competencies that they believed were most important for promoting D&I in the fleet. Inclusive leadership emerged as a dominant theme; in particular, participants felt most included in commands where leadership valued their perspectives and ideas and where Sailors felt heard on a day-in, day-out basis.

Keywords: diversity, inclusion, competency model, training

Background
The overarching goal of this study is to understand how to best assess diversity and inclusion in the fleet. Prior work (Arkes et al., 2020) examined how greater diversity on ships affected retention of Sailors from traditionally underrepresented groups. Their quantitative study found evidence that, for black Sailors, having more peers and superiors of the same race/ethnicity led to a greater likelihood of reenlisting. Their qualitative study, using data collected through interviews, found that the main reason retention was lower in less diverse environments was a diminished sense of belonging among members of underrepresented groups.

In our study, we aimed to further investigate factors that contribute to experiences of inclusion or exclusion in the fleet and to develop a survey instrument for assessing D&I in Navy commands.

Our research objectives were the following:
1. Develop metrics to assess behaviors of inclusion within the fleet.
2. Assess inclusion behaviors within the fleet using the developed metrics.
3. Determine which D&I competencies are the most impactful for building inclusion.
4. Determine what command practices and policies contribute to greater acceptance of diversity.

Our metrics of D&I were based on accepted best practices for promoting inclusion in organizations as well as validated/established questionnaires for assessing D&I, which we tailored to the context of the Navy and Sailors’ work. The study builds directly from Arkes et al.’s (2020) qualitative study, which involved ship interviews with 45 first termers about their experiences with D&I. Our study uses insights derived from those interviews to develop a survey tool for assessing Personal Inclusion Factors (individuals’ feelings of being personally included within their command) and Command Core Inclusion Competencies (individuals’ beliefs about how their commands demonstrate diverse and inclusive practices) suitable for assessing D&I climate in the fleet.

To assess inclusion behaviors in the fleet, we administered the survey to two groups of participants: officers attending the Naval Postgraduate School and members of a closed Facebook group for Navy
Officers. A total of 617 participants (NPS students and the Facebook Naval Officers group) responded to the survey. Of these, 489 responses were retained for data analysis, having responded to at least some of the diversity and inclusion questions. Participants rated both their current and past commands on Personal Inclusion Factors and Command Core Inclusion Competencies. The sample consisted of a wide variety of experience levels in the Navy, with a larger fraction of female and officer respondents. The group is predominantly a white sample but includes respondents from several traditionally underrepresented race/ethnicity backgrounds.

To determine which D&I competencies are most impactful for building inclusion, participants responded to open-ended questions and ranked various D&I competencies according to perceived importance.

Collectively, the study identifies command practices either currently in place or that can be implemented to promote the Navy’s D&I efforts.

**Findings and Conclusions**

For the Personal Inclusion Factors, questions with the strongest factor loading (indicating a larger contribution to feelings of personal inclusion) were *My opinion is valued by my supervisors for important decisions* and *My experiences at the command made me believe I have equitable opportunities for a future in the Navy*. The item assessing fair distribution of outcomes (training opportunities, awards, recognition, and leadership opportunities), although important, had the weakest factor loading. For the Command Core Inclusion Competencies, the questions with the highest factor loading were *Demonstrate respect for others’ values and customs*, *Acknowledge cultural differences*, and *Check [oneself] for personal biases*. For our primary analyses, items comprising the two respective scales were averaged, resulting in two scores for each command, present and past.

Many of the patterns reflected in our data track with broader themes and issues the Navy is currently tackling. When looking at personal inclusion, in general, men tended to feel stronger personal inclusion in their commands (present and past) than women. This largely held true across different race/ethnicity groups, paygrades, and years of service. Women’s feelings of personal inclusion tended to increase proportionate to their tenure in the Navy.

For the Command Core Inclusion Competencies, men tended to rate commands as more inclusive than women. Similarly, members of underrepresented groups tended to rate commands as less inclusive than White respondents did. Differences between men and women in ratings of Command Core Inclusion Competencies were more pronounced in sea versus shore commands. Our results suggest that shore commands were, on average, more inclusive for women than sea commands.

Participants ranked Command Core Inclusion Competencies according to their perceived importance for promoting a diverse and inclusive command. The most important items were *listening carefully and considering others’ perspectives and demonstrating respect for others’ values and customs*. In open-ended responses, the most prominent theme across demographic groups was that inclusion entails feeling valued and heard on a day-in, day-out basis. D&I was seen largely as a “leadership problem”—something that was supported (or eroded) by leadership practices that actively included (or excluded) individuals up and down the chain of command. Interestingly, equity of outcomes and opportunities did not factor strongly into respondents’ sense of an inclusive environment.
In conclusion, both personal inclusion and command competency metrics suggest that commands that tend to do better (or worse) on one aspect of D&I tend to do better (or worse) on most/all other aspects. Despite emphasis on D&I initiatives, there remain “inclusion” gaps between underrepresented and majority Sailors, particularly at sea. Educating and developing Navy leaders who are adept at promoting inclusion throughout the command is one step the Navy can take to respond to themes surfaced by participants’ responses to our survey. Our respondents looked to their leaders to set the norms and expectations for D&I in their respective commands. Leaders who showed that they valued Sailors’ unique experiences and knowledge and who engaged people across the command in decisions (where appropriate) were critical to respondents’ sense of inclusion.

**Recommendations for Further Research**

Sailors look up at their leaders to set the norms and expectations for diversity and inclusion (D&I) in their respective commands. To support the Navy in educating and developing leaders who are adept at promoting inclusion throughout command, one future study could examine whether educating leaders about concrete, actionable D&I-promoting behaviors and practices carries a lasting impact for Sailors’ perceptions of D&I in their commands. Measuring the impact of concrete practices on the broader D&I climate is an important next step toward prioritizing the Navy’s D&I efforts over the short-, mid-, and long-term.

**References**


**NPS-21-N330-B: Nuclear Officer Bonus & Incentive Pay (NOBIP) and Retention**

**Researchers:** Dr. Judith Hermis, Dr. Robert Eger, and Dr. Spencer Brien

**Student Participation:** No students participated in this research project.

**Project Summary**

Retaining top-quality nuclear officers is critical to mission readiness. To facilitate officer retention, the Navy offers a bonus, the Nuclear Officer Continuation Bonus (COBO), to officers who have fulfilled the minimum service requirement (MSR). The Navy recently raised the amount of the bonus in the hope of increasing retention. It is mission-critical to understand how responsive retention rates have been to COBO, particularly in light of the recent changes. This study examines the efficacy of the most recent bonus policy for nuclear officers, NAVPOL 20241, and its immediate predecessor. Specifically, we used sponsor-provided data on 2,058 nuclear officers across seven-year groups to assess the impact of the latest NAVPOL on nuclear officer retention relative to the immediately prior policy. Statistical analyses using survivorship modeling revealed that individual characteristics, such as the overall unemployment rate, marital status, presence of dependents, length of military tenure, and membership in certain racial/ethnic groups are all positively and statistically significantly associated with nuclear officer retention.
We recommend the Navy commission additional studies to obtain a deeper understanding of the non-monetary factors influencing nuclear officer retention, rather than a simple increase in the dollar amount of the COBO.

**Keywords:** retention, bonuses, officer pay, compensation, turnover

**Background**

Retention of high-quality nuclear officers is critical to Fleet readiness. The Navy recently adopted a new bonus pay scheme for nuclear officers, NAVPOL 20241, because anecdotal evidence suggests that the predecessor policy, which was also adopted to increase retention, did not fully achieve the desired effect. It is important to the Navy to understand changes in nuclear officers’ decision making and turnover decisions in response to changes in COBO. The Navy has faced a historically competitive job market with regard to retention of the best nuclear officers. It is mission-critical for leadership to understand how historical trends and new pressures due to the COVID-19 pandemic mitigate or enhance the effects of the COBO compensation plan.

Prior literature has explored the impact of monetary and qualitative factors on the recruitment, retention, and job satisfaction of military personnel (e.g., Lewin Group, 2007; RAND, 2012; RAND, 1996; RAND, 1993). Additionally, an extensive body of literature in accounting, corporate finance, and economics addresses the role of compensation in incentivizing certain behaviors among economic agents (Coughlan & Schmidt, 1985; Hadlock & Lumer, 1997; Murphy, 1999; Desai et al., 2006). Extant research in managerial and defense compensation provides a natural foundation on which to build a study about current COBO practices.

To address the above concerns regarding retention, we first performed an in-depth literature review of economic, finance, accounting, and management literatures on compensation. We then used sponsor-provided data, combined with the latest research findings, to design an empirical study of the impact of NAVPOL 20241 on nuclear officer behavior. We created a model of professional survivorship based on employment policy theory, prior research, and input from the sponsor. For example, our model included controls for personal officer characteristics such as age, military tenure, race, and marital status, as well as characteristics of officers’ prior experiences with the Navy before signing the Department Head (DH) contract, including the location of the Department Officer Tour (DOT), the type of vessel on which the DOT was performed, and whether the vessel was in the shipyard during the officers’ DOT. While the data contained information on the entire length of the officers’ careers, this analysis focused particularly on the time immediately following the point that the officers passed their assessment, as this was a likely period when the officers’ views on whether to remain in the Navy and continue as a department head were established. Additionally, the model includes the unemployment rate and the locality of the officers’ homeport to control for effects of the regional economy.

The analysis employed data from 2,058 individual nuclear officers spanning year groups 07 through 13, with relatively even distribution of officers across the year groups. The sample of Nuclear Officer personnel data was obtained directly from the sponsor. The model describes the likelihood that an individual officer would sign a DH contract given their personnel characteristics.
The model was estimated using logistic regression.

**Findings and Conclusions**
The estimates obtained from the logistic regressions identified several individual characteristics that have a statistically significant relationship with the likelihood of signing a DH contract. Age, prior enlisted service, marital status, and having dependent children at the time of passing were all positively associated with signing a DH contract. A higher unemployment rate in the macroeconomy was also positively linked with the likelihood of signing. Officers who served their DOT on certain types of ships were less likely to sign than those who served on other vessels.

We also thoroughly examined the hypothesis that serving a DOT aboard a ship that was in the shipyard impacted retention rates. Ultimately, we found no evidence within our sample to support the argument that time in the yard affects retention.

The analysis was replicated with a smaller data set of Surface Warfare Officers (SWOs); empirical results revealed that observed associations between the above-described characteristics for nuclear officers were subsumed by year-group membership for SWOs. The SWO analysis did not reveal any findings that were not consistent with the larger study of submarine nuclear officers. Variations in retention for SWOs appeared to be largely driven by year groups for this subset of naval officers.

Taken together, these results suggest that the dollar value of the COBO bonus may not be sufficient to fully explain nuclear officers' retention decisions. Extensive prior research finds a weak association between compensation amounts and retention decisions in the public sector, while a stronger association can be found between soft factors (such as sense of efficacy and job satisfaction) and retention decisions. Given the budget reductions currently facing the Navy, we recommend the Navy further explore the non-monetary factors associated with nuclear retention as an additional mechanism to meet their staffing goals.

**Recommendations for Further Research**
Further research can explore and identify the non-monetary factors associated with nuclear officers and Surface Warfare Officers retention. Survey research would be useful to understand these factors. We recommend the Navy enhance non-monetary factors associated with officer retention rather than increasing the size of the Nuclear Officer Continuation Bonus, as cash compensation alone is unlikely to fully meet the Navy’s retention goals. We also recommend the Navy separately examine the impact of compensation models on the retention of enlisted personnel, as their background and career trajectory significantly differ from those of officers.

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**NPS-21-N333-A: Evaluation of Leadership Traits for Future Warfare**

**Researchers:** Dr. Mark Nissen and Dr. Simona Tick  
**Student Participation:** LCDR Gabriel Caldwell USN and LCDR Frederik Auliveld USN

**Project Summary**
The Navy recognizes the continuing need to develop warfighters able to lead using critical problem-solving skills while fostering an environment of trust throughout the command. Recent research suggests that leaders must be fluent in skills like humility, empathy and perspective taking. However, very few tools are available to help leaders improve their effectiveness in these areas. This study focuses on understanding the elements of *humility* and how they interrelate with, complement and supplant other important leadership traits required for future warfare. Building on the literature review, we consider the dynamics of knowledge to show how the Navy can develop important leadership traits such as *humility*. Based on our findings, we address how *humility* can be integrated into knowledge flows in the Navy leadership training to prepare its current and future warfighting leaders.

**Keywords:** humility, soft skills, leadership, training

**Background**
Recent research suggests that leaders must be fluent in skills like humility, empathy and perspective taking. Indeed, *humility* stands out for many researchers as a particularly effective leadership trait, one that is suited ideally for leadership in the current age of intelligent, autonomous systems integrating persistently into our professional lives.

The primary objective of this project is to focus on understanding the elements of *humility* and how they interrelate with, complement and supplant other important leadership traits required for future warfare. Three research questions provide focus: 1) What are the key elements of *humility*? 2) How do the elements of *humility* interrelate with, complement and supplant other important leadership traits required for future warfare? 3)
How can humility be measured to support Navy development of leadership traits required for future warfare?

The research method begins with a purposefully focused literature review. This review includes books, articles and documents about leadership and humility (e.g., Hess & Ludwig, 2017; Hu et al., 2018; Hyman, 2018; Ou et al., 2014, 2018). Humility emerges as an important leadership attribute, but although necessary, it does not appear to be sufficient. Rather, in conjunction with emotional intelligence and other factors, research to understand, measure and apply humility appears to offer excellent promise to enhance leadership and help the Navy continue to progress from good to great.

Humility is also noted as a leadership foundation in the Navy Leadership Development Framework (Office of the Chief of Naval Operations, 2019). Moreover, Hess and Ludwig (2017) address humility in great depth, asserting that organization agility, adaptability, and responsiveness are becoming more important than efficiency. This leads to four key behaviors: Quieting Ego; Managing Self (one’s thinking and emotions); Reflective Listening; and Otherness (emotionally connecting and relating to others; p. 33).

Building further on Knowledge Flow Theory (KFT; see Nissen, 2014), we employ comparative analysis to understand humility in Navy leadership better. More specifically, this involves assessing key leadership traits within the Navy Desired Leadership Attributes (NDLAs) as well as new traits such as humility, which we compare to the material being taught to prepare junior officers for Division Officer leadership (especially the Division Officer Leadership Course or DIVOLC). This provides the grist for knowledge flow analysis via KFT concepts, tools, and techniques. Thus, we use the NDLAs as a proxy for current leadership emphasis and the DIVOLC for corresponding training.

Findings and Conclusions
Key findings indicate that the NDLAs address core values, moral character, judgment and leadership, whereas the DIVOLC addresses communication, moral character and teamwork. Although we find some correspondence between the two (especially common emphasis on moral character), neither appears to address humility directly. Hence, we see an opportunity to update and expand both to address humility as part of advancing leadership efficacy in the Navy.

Humility knowledge flow analysis builds then upon these findings to examine and delineate four knowledge flows: 1) DIVOLC training lessons, 2) DIVOLC curriculum, 3) on the job training and 4) coaching. Such analysis results in three recommendations: 1) Introduce humility training into the DIVOLC; course instructors will likely require assistance with this. 2) Division Officers should have continued access to humility course content to prevent their classroom knowledge from growing stale or even perishing; humility will likely have to be mandated, modeled, incentivized and reinforced from the top. 3) Encourage leaders to coach subordinates; such coaching can promote and support humility.

Recommendations for Further Research
One or more follow-on studies can build upon these findings and recommendations. One such study would expand the purposefully focused literature review and draw from other leadership perspectives. Another could incorporate additional training courses into the analysis. A third could examine where and how well coaching occurs across the fleet. A fourth, and more proactive, study could work to assist Division Officer Leadership Course instructors with integration of humility material into their
coursework. This is likely to have the greatest immediate benefit and represent the highest return on investment.

References


NPS-21-N351-A: Social Network Analysis on Connectedness, Destructive Behaviors, and Effects on Stress

**Researcher:** Dr. Ruriko Yoshida  
**Student Participation:** LT Vanny Mae Angeles USN

**Project Summary**
Substance abuse remains a significant problem among Sailors within the United States Navy. Excessive use of alcohol and drugs can be detrimental to a Sailor’s health, safety, and naval service. The U.S. Navy recognizes that substance abuse is preventable and treatable and aims to eliminate these destructive behaviors through continuous training, intervention, and treatment. However, the need to address alcohol and drug abuse using an alternative approach arises as Sailors continue to exhibit these destructive behaviors. We propose the use of supervised machine learning methods complemented by social network analysis to explore alcohol- or drug-incident data from the Alcohol and Drug Management Information Tracking System (ADMITS). Under our method, we build prediction, classification, forecasting, and generalized network autoregressive (GNAR) models to provide insights on the correlations between Sailors' backgrounds and their alcohol- or drug-related incident information. We utilize performance assessments for regression, classification, and time-dependent data to measure the accuracy of our models and to identify which perform best. Our results strongly demonstrate that the use of supervised machine learning methods provide an accurate and effective approach to modeling and further understanding the different aspects of substance abuse among Sailors.
**Keywords:** alcohol-drug abuse, alcohol and drug management, classifications, machine learning, social network analysis, supervised learning, time series analysis

**Background**

The Department of the Navy (DON) recognizes that alcohol and drug abuse are preventable and treatable conditions (Office of the Chief of Naval Operations [OPNAV], 2009). Screening, referral, early intervention, treatment, and continuing care services for alcohol and drug abuse are services available to all USN members. On June 2013, the DON established the OPNAV N17 branch, also known as the 21st Century Sailor Office (Vice Chief of Naval Operations [VCNO], 2013). OPNAV N17 comprises several departments that aim to establish a more efficient way of providing USN members support regarding Sailor resiliency and readiness programs, such as substance abuse prevention, suicide prevention, and the Substance Abuse Rehabilitation Program (SARP) (VCNO, 2013).

A priority for the N17 organization, among many others, is to be able to identify Sailors who exhibit at-risk behaviors of substance abuse and to understand the underlying causes of these destructive behaviors. OPNAV N17 is able to monitor alcohol and drug abuse and misuse Navy-wide using a database known as the Alcohol and Drug Management Information Tracking System (ADMITS). ADMITS is the “Navy and Marine Corps repository for alcohol and drug incident, screening, treatment, and training information” (OPNAV, n.d., para. 1). USN commands submit Drug and Alcohol Reports (DARs) that feed Sailor and incident information into ADMITS. The database supports the USN’s ongoing approach to eliminating alcohol and drug abuse by providing statistical reports regarding the efficacy of current substance abuse programs and the urinalysis testing policy (OPNAV, n.d.).

Applications of machine learning (ML) methods in substance abuse research have emerged as an effective approach to studying substance-related incidents and the risk behaviors associated with them (Hu et al., 2019). Specifically, social networks, time series forecasting, and other supervised ML algorithms have been leveraged to predict alcohol- or drug-related incidents and identify key attributes that potentially influence these destructive behaviors (Hu et al., 2019). The ability to identify, predict (or classify), and forecast substance use and risk behavior among a group of individuals can help with monitoring the trend of alcohol- or drug-related incidents. Forecasting and monitoring are particularly important in identifying individuals at risk for substance abuse and informing policy changes within organizations.

Here, we apply a combination of supervised ML methods and social network analysis (SNA) to historical data obtained from ADMITS to gain an improved understanding of the potential risk factors contributing to destructive behaviors among Sailors within the USN.

This research employed several ML methods to better understand substance abuse and the potential risk factors that contribute to destructive behaviors among Sailors within the USN. We built prediction, classification, forecasting, and GNAR models using data from the ADMITS database to provide insights on the correlations between Sailors' backgrounds and their alcohol- or drug-related incident information. To assess our methodology, we utilized predictive performance measures for regression, classification, and time-dependent data. We compared each model's predictive performance using their respective performance measure to identify which models performed best.
Findings and Conclusions
Our results strongly indicate that supervised ML methods provide an accurate and effective approach to modeling the different aspects of substance abuse, particularly among Sailors within the USN. By employing feature importance, we were able to identify that the status of driving while intoxicated/under the influence, SARP’s recommendation for treatment, a particular incident’s information, the reason why a particular member was referred to SARP for screening, substance’s name, and the state where the person is located were the most useful attributes in (1) predicting the number of alcohol- or drug-related incidents committed by a particular Sailor, and (2) classifying whether or not a particular Sailor will repeat an alcohol- or drug-related incident.

The seasonal Auto Regressive Integrated Moving Average time series forecasting model results demonstrate its ability to accurately model and subsequently forecast the total number of monthly alcohol- or drug-related incidents for a given time range. Additionally, the logistic regression classification model performed the best overall in classifying whether a particular Sailor will repeat an alcohol- or drug-related incident. Finally, predictive performance measures for the GNAR model with modified parameters suggest its capability to effectively model when a particular Sailor will commit and/or repeat an alcohol- or drug-related incident. As a result, these models have exhibited predictive power and are viable for further analysis.

Recommendations for Further Research
The models built in this research provide a baseline for future studies, and their accuracy demonstrates the effectiveness of Machine Learning (ML) methods in substance abuse research within the United States Navy (USN). ML models have much potential in what they can offer, especially with regard to providing insights that can influence command-wide decisions. To further leverage the advantages of ML, additional efforts could be made to improve this study’s models or develop more advanced predictive applications that can detect current abuse, assess future risk, or predict treatment success.

According to Barenholtz et al. (2020), future alcohol and drug abuse studies that incorporate ML methods will likely see promising results from the use of modern deep neural network models. Currently, modern deep neural networks, such as convolutional neural networks (CNNs), are not often used in substance abuse research (Barenholtz et al., 2020). These complex ML methods have shown success in modeling unstructured data and provide the means for future studies to include multiple data sources, new data types, and new model architectures—all of which are not possible with previous ML techniques (Barenholtz et al., 2020).

This study did not implement data transformations or steps to normalize attribute values during the model fitting process. Normalizing values allows equal weights to be distributed among each variable so that no single variable skews model performance due to its large value. For example, it would be useful to present alcohol- or drug-related incident counts normalized by the size of their respective department since larger departments are expected to have greater numbers. Moreover, proper data transformations can improve data quality and the overall efficiency of the analytic models.

When building the social network structure for the generalized network autoregressive (GNAR) models, we considered a static network where we assumed all Sailors entered and exited the network at the same time.
A future study could explore the effects of Sailors joining and leaving the social network based on their report date entered into the Alcohol and Drug Management Information Tracking System (ADMITS) and whether they were still on active duty service. Additionally, the social network’s adjacency structure can be modified when establishing an edge (or connection) between two Sailors. Rather than drawing an edge based on whether two Sailors share a common attribute, a hierarchical approach can be utilized instead. For example, an edge would be established between two Sailors only if they are located within the same state, command, and department (in that order).

References


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N2/N6 - INFORMATION WARFARE

NPS-21-N032-B: Multi-Domain Information Fusion: What Makes a Good Fusion?

Researcher: Dr. Eva Regnier
Student Participation: No students participated in this research project.

Project Summary
With the goal to provide guidance on information-acquisition decisions—encompassing collection, processing and communication decisions—to ease the cognitive workload in the information warfare (IW) community and for other warfare commanders, this work analyzed critical command decisions (CCDs) and the information-acquisition systems that support them in light of decision analysis and cognitive science knowledge and practice.

Even for simple CCDs, critical variables that may be uncertain (unknowns) including background threat, red capabilities, blue capabilities, sensor performance and vulnerabilities affect which course of action (COA) is better, which information is more valuable, and how information including sensor data should be interpreted.

Many variables that affect CCDs and information-acquisition decisions can and should be estimated by human analysts, and be communicated to the machine—the interfaces between humans and machines in a highly effective battle information network would be two-way. Human analysts can also contribute in generating scenarios and parameters for simulations to produce synthetic data to train the machine for future, not-yet-observed scenarios.

Probabilistic reasoning should be done by machine as much as possible to avoid common and serious cognitive errors. Moreover, there are many important advantages to structuring battle networks around a probabilistic (Bayesian) network, and events during the period of performance have made these advantages even more prominent.

When information-acquisition decisions can’t be made based on relevance to a CCD, a qualitative approach to identifying high-value opportunities for fusion is needed. When prioritizing information sources for collection, processing, or communication, a pair of information sources—or, existing information and a new potential source—should be evaluated in terms of their commonality with respect to attributes including domain, sensor type, vulnerability and common cause.

Keywords: information dominance, decision analysis, cognitive errors, probabilistic network, Bayesian network, critical command decision, CCD, course of action, COA, value-of-information, VOI, meteorology and oceanography, METOC

Background
Decisions in the battlespace are becoming more complex—more information, more alternatives that require coordinating diverse assets and forces, more rapidly evolving red capabilities, and all of this increasing exponentially with the addition of domains of operation–space, the electro-magnetic spectrum, even public opinion. However, when the speed of decisions is measured in seconds, CCDs will need to
Only a few major COAs can be considered, with details worked out well in advance and/or largely by machine. Time and cognitive constraints mean the human decider can take in only a small amount of new information at decision time. These decisions will also be difficult with high stakes and no clear best answer. If this simplification—structuring and analyzing critical decisions—is not done in advance, it will be done in real time in an ad hoc manner because the commander is overwhelmed, and decision quality will suffer.

A common pitfall when information is not analyzed in terms of its value for decision support is that information is fused based on criteria such as similarity of format or source, and based on similarity of mission, rather than based on their contribution to key actionable information. Information from intelligence, physical environment data, and communications all inform each warfare area, and their implications for decisions interact in highly complex ways.

We reviewed documents regarding the IW community and watchfloor as well as literature on cognitive science and engineering and prescriptive decision analysis. We used value-of-information (VOI) analysis on stylized examples of CCDs and information-acquisition decisions to identify key insights and recommendations.

**Findings and Conclusions**

Even for the most minimal archetypal CCD—shoot the possible target or don’t shoot based on an imperfect sensor signal—the interactions and probabilistic relationships among key unknowns mean that it is challenging and probably not useful to define a single actionable informational input. However, to support quality CCDs when the speed of decisions is measured in seconds, information must be provided that can move the commander in the direction of confidence in the selected COA, even without providing certainty. With the goal of increasing decision confidence, the best information-acquisition decisions can be very counterintuitive.

Current limitations of machine intelligence leave some critical roles for humans in the networked battle system, such as identifying novel scenarios on which the machines should be trained and synthesizing certain kinds of information that is novel and/or not digitized, including information about threat, and red capabilities. These and other variables that are assessed by human judgment heavily influence how data, including sensor data, should be interpreted, and which information source is more valuable. Therefore, subject-matter experts’ judgments regarding key unknowns so they can be communicated to the machine, using knowledge-elicitation practices from decision analysis, can be used to quantify subject-matter experts’ judgments regarding key unknowns.

Public reports of the vulnerability of a centralized command and control system in combat wargames undermine the vision of Joint All-Domain Command and Control (JADC2) that depends on sending all relevant data in real time to a common lake to let the machine sort it out. This suggested some important advantages using a Bayesian network approach to the architecture of battle networks, instead of other major AI approaches. Among other advantages, a Bayesian network supports fusion of information regardless of source—including human expert judgment (e.g., regarding adversary intent or capabilities); it dramatically reduces the requirements on data links, with respect to bandwidth, continuity of connectivity, and even transmission mode—at the limit, one or more numbers sent verbally by radio can be used to summarize sensor inputs and update situational awareness to support CCDs.
When the information-acquisition decisions can’t be made based on relevance to a CCD (e.g., when assets are being designed or acquired so data are not available to quantify the relationships among information sources), a qualitative approach to identifying high-value opportunities for fusion is needed. The analysis in this project suggests that when prioritizing information sources for collection, processing, or communication, a pair of information sources—or, existing information and a new potential source—should be evaluated in terms of their commonality with respect to: Domain and geographic location; Timing/latency; Collection method (i.e., sensor type for sensors); Vulnerability to jamming, spoofing or other red interference; Meteorology and oceanography (METOC) sensitivity; and Cause/scenario.

If the sources are more diverse with respect to these attributes, they are more likely to be independent or complementary. This perspective implies some counterintuitive criteria for information value. For example, source accuracy is not necessarily the primary driver of value.

**Recommendations for Further Research**

By organizing the information system—and battle network—around decisions, and by using what is known about optimal and human decision making to make good design choices, we can build more effective systems and avoid costs and pain down the road.

This project explored the implications of an analysis of what makes information actionable in a critical command decision (CCD) and how information-acquisition decisions can be made to support high-stakes low-seconds decisions. A next step towards operationalizing the concepts described here would be to develop in more detail a structure of a specific CCD and model portions of the information that would support it.

For the development of Project Overmatch, other elements of Joint All-Domain Command and Control and/or other networked information systems, the findings of the report indicate that exploring a probabilistic network architecture is indicated. Such a system may exploit neural networks and other non-probabilistic computations in edge computing and in constructing and training the system. However, in real-time and especially in degraded or non-secure communications, a system constructed around a modeled probability network would be able to exchange critical information and update the situational awareness of the entire system more rapidly and effectively.

**NPS-21-N037-A: Cyber Warfighting System for Resilience and Response**

**Researchers:** Dr. Scott Jasper and Mr. Jack Turner  
**Student Participation:** MgySgt Travis Hollingshead USMC and MSgt Lorenzo Rucker USMC  

**Project Summary**

The Cyber Warfighting System project aims to provide an automated capability to recognize and declare the threat to set appropriate resilience and readiness postures. Organizations use an incident response methodology to respond to and manage the effects from a cyber-based intrusion event. Rapid and accurate identification of intrusions and the implementation of adequate response methods to reduce the impact upon operations and recover system functionality and security quickly remain a priority for all
organizations reliant upon digital networks. Identifying potential defensive gaps, constraints, and resource limitations during the execution of incident response remains a critical requirement for Department of Defense (DoD) organizations. In 2021, the Naval Postgraduate School (NPS) studied and analyzed cloud-based cybersecurity platforms that provide security orchestration, automation, and response capabilities.

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

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

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

In 2021, NPS studied and analyzed cloud-based cybersecurity platforms that provide security orchestration, automation, and response capabilities.

**Findings and Conclusions**
The findings and analysis are contained in the MACO student capstone thesis (Hollingshead & Rucker, 2021). Distribution of the thesis is authorized to DoD and U.S. DoD Contractors only.

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

**References**

**Project Summary**

The U.S. Navy’s Earth Systems Prediction Capability (ESPC) provides value exceeding the value of climatology at subseasonal to seasonal (S2S) lead times for key impact variables and operational limits for certain regions’ seasons. This project used value-of-information (VOI) analysis and data farming, together with ESPC reforecasts produced as part of the subseasonal experiment together with a reanalysis data set for verification and climatology, to conduct an automated global search for regions, seasons, operational limits, and other decision parameters that produced a high VOI. This flips the script on looking for users—high-value scenarios are identified first, then the search for users who correspond to the scenario’s parameters can begin.

Through outreach to Meteorology and Oceanography (METOC) personnel and users, we mapped mission and decision contexts to the variables and appropriate structure for VOI analysis. While missions that involve transit, such as ship routing, require more complicated models, many important mission sets can be represented using straightforward extensions of a single-variable, binary METOC outcome, binary decision (1 x 1 x 1) cost:loss decision scenario, in particular by adding multiple decision stages, and multiple forecast and operational impact variables.

For example, decisions on preparation for adverse METOC at shore installations, e.g., tropical cyclone conditions of readiness, can be represented with a modified 1 x 1 x \( n \) cost:loss scenario where the outcome depends on \( n \) valid times. For Arctic operations, surface and air temperature and winds are all important, and combinations of these variables are very important. For some missions, however, an \( n \) variables x 1 x 1 scenario can be used. Similarly, for underway replenishment, winds and waves are most important, but using a 2 x 1 x 1 model can be used when neither combat nor logistics vessels have a long transit. Preparation for climate extremes, e.g., of temperature or precipitation, can be represented with a 1 x 1 x 1 scenario by aggregating valid times and locations.

**Keywords:** decision science, decision-making, data farming, meteorology and oceanography, METOC, Earth Systems Prediction Capability, ESPC, subseasonal to seasonal, S2S

**Background**

The United States Naval meteorology and oceanography (METOC) community seeks a better understanding of when, how, and to what extent Naval METOC guidance, forecasts, and advice can improve decision-making. This understanding is critical to determine how best to collaborate with the broader Navy and Marine Corps, and to guide investments in future research and training.

Commonly, when METOC researchers develop capabilities and resulting forecast products, they reach out to the user community with open-ended questions about what products would users find most valuable.
This can work well, especially for identifying products "near" existing products that are relatively easy for users to understand and integrate into their current decision processes. Users, however, often cannot anticipate how they will use an innovative product until they have it in their figurative hands.

Our novel approach combines value-of-information (VOI) analysis with data farming (Sanchez & Sanchez, 2017) to conduct a very broad and automated search for combinations of end-user parameters for which potentially available forecasts can produce high value in decision making. These results can be used to identify candidate products that combine variables or exploit subseasonal to seasonal (S2S) predictability provided by the Navy's Earth Systems Prediction Capability (ESPC) (Barton et al., 2019) and end-users who could exploit these forecasts.

We used ESPC reforecasts from the Subseasonal Experiment (SubX) experiment with lead times up to 1,062 hours (45 days) to represent the capabilities of the European Centre for Medium-Range Weather Forecasts (ECMWF), together with verifications and climatology from the ECMWF reanalysis, for 2-m temperature, sea surface temperature, 10-m winds, sea ice concentration, total cloud cover and spray icing prediction index. We coded a flexible cost:loss decision scenario and used data farming to explore regions, seasons, operational limits and other decision parameters that produced a high value-of-information (VOI).

Through outreach to METOC users, we mapped mission and decision contexts to the variables and appropriate structure for VOI analysis.

**Findings and Conclusions**

We identified clear benefits of ESPC extended-range forecasts as a function of METOC variable and user parameters. Although we anticipated that the value of S2S forecasts is affected by the manner in which shorter-range forecasts are used to adjust decisions (Regnier, 2008), we found that for many parameter combinations, the impact of the short-range decisions was lower than anticipated.

A better understanding of when, how and to what extent Naval METOC guidance, forecasts, and advice impacts decision-making in the Navy is critical to N2/N6 to guide investments in future research, training, and collaboration with the broader Navy and Marine Corps. This research supports the 26 March 2020 Oceanographer of the Navy (OPNAV N2N6E) Fiscal Year 2021 Research, Development, Test and Evaluation Priorities (Paragraphs 3e and 3f).

As detailed in the project summary, ESPC forecasts have the potential to improve decisions in many critical missions. Missions that involve transit, such as ship routing, require more complicated computations; many important mission sets can be represented using simpler models. Straightforward extensions of a single-variable, binary METOC outcome, binary decision (also called atomic or 1 x 1 x 1) cost:loss decision scenario, in particular by adding multiple decision stages and multiple forecast and operational impact variables, cover many mission contexts, as detailed in the Project Summary.

Because short-range forecasts are more accurate than extended-range forecasts, when decisions can be delayed, they can exploit higher-accuracy forecasts. Decisions that cannot be delayed will exploit extended-range forecasts. These decisions typically share the following characteristics:
• involve slow-moving assets such as ships and many logistics decisions;
• take a long time to implement, are costly, and therefore only undertaken for a rare METOC event;
• are relatively more complex, as many more decision variables are undetermined at longer lead times, and therefore the details of extended-range decisions are less well-defined; and
• further decisions that can be taken at shorter-range lead times substantially influence the outcome of extended-range decisions.

Naval missions that can benefit from extended-range forecasts include:
• ship routing, in particular for logistics and in the Arctic;
• positioning assets regionally; and
• preparation for extreme events at fixed geographic locations.

In addition, Naval missions that can benefit from extended-range forecasts almost always involve short-term flexibility and, in particular, may include the ability to move operations geographically and temporally with shorter lead times—for example, postponing air operations or underway replenishment for hours or days, or moving operations a few tens or hundreds of nautical miles.

The ability to exploit geographic flexibility at both extended and short lead times is much more typical of Naval missions than civilian and commercial decision contexts. With the exception of preparing for extreme adverse events, civilian and commercial decisions that exploit extended-range forecasts often involve temporal flexibility—decisions about when to schedule an operation, or timing of water resource management decisions such as drawing down reservoirs. This indicates that Naval missions benefit from Navy-focused investigation of S2S forecast value.

**Recommendations for Further Research**

The current project showed that the Earth Systems Prediction Capability (ESPC) can provide high value—for some regions, seasons, and operational limits. The extended-range forecast capability is new, and therefore new products can be developed and presented to users. We recommend developing a tool or tools to help operational forecasters interactively identify high-value products so they can use that information to choose products to use and develop tailored products for specific end-users and even specific missions. Although the current project was limited by the variables and other limits in the subseasonal experiment data base, it does provide a method and algorithms, and at least a preliminary code base, for such a tool. There is a substantial value to be exploited by using newly available capabilities and existing forecasting capabilities that have not yet been incorporated into mission-planning and shorter-range decision processes. Finding and exploiting these opportunities requires a productive interaction between end-users and the METOC community (Regnier & Feldmeier, 2021), and operational forecasters are in an ideal position to be able to identify these opportunities.

While many missions can be represented by the decision scenarios explored in the current project, missions that involve transit, such as ship routing, require more complicated computations. We recommend using the VOI and data farming approach, together with existing mission planning models, such as the Replenishment at Sea Planner developed at NPS and optimal-track ship-routing algorithms, both in use and under development at the Naval Research Laboratory, to assess the value of adding both short and extended-range (ESPC-derived) forecasts to these models.
Both the approach and code base developed in this project can now be used to explore the value of ESPC forecasts for variables not available for this project, such as waves. They can also be used to answer questions of interest to the METOC community regarding forecast product development such as choice of ensemble summary (mean and standard deviation vs. percentiles); frequency and size of ensembles for ESPC and other forecasting models; and alternative ways of combining variables, including identifying new indices (analogous to El Niño-La Niña indices) with high predictive value.

References

NPS-21-N124-A: Leveraging Commercial and Other Innovation for Future USN Data, Information, and Intelligence Needs [NECC Focus]

Researcher: Mr. Arijit Das
Student Participation: Ms. Kaylin Li CIV INT and Ms. Aroshi Ghosh CIV INT

Project Summary
Information is gathered and processed by the Intelligence community, and summarized in the form of reports, which grows over time; thus, there is a need to search for content (over history) in a smart manner. This project found that existing software solutions available via Department of Defense (DoD) licenses and Open Source meet the requirements for document search options using computer science–based software technologies.

Keywords: Naval Expeditionary Combat Command (NECC), naval expeditionary combat forces, domain awareness, tribes, information stream, intelligence gathering, reports, document relevance, database schema design, Hadoop, Apache Webserver, 3-tier architecture

Background
The Naval Postgraduate School researchers worked in an earlier Naval Research Program–funded project for the Mine Warfare community where they analyzed sonar data (and the growth of it) for analytics. The same community in this effort shifted focus to the reports generated by the various Department of Navy (DoN) commands (Naval Expeditionary Combat Command [NECC] focus) and the challenges faced in the searching of documents.
At the very outset, there was a need for a Subject Matter Expert (SME) to guide the team on where and what to look for. The SME is also a Point of Contact who identified the Commands to interview and discuss their data analysis challenges. The focus was to keep the effort in the unclassified domain as much as possible and only go over to the classified side on a need basis. A couple of Zoom/Teams/phone meetings led to discussions, and the knowledge gathered set the stage for the exploration of applicable technology.

Raw intelligence data is usually summarized into reports (standard format files), which need to be stored for retrieval and search. A few of the financially viable choices are Hadoop Distributed File System (HDFS) for very large volumes and a database (Oracle vendor) for mid-sized volumes. The next consideration was gathering metadata that will assist in the fast retrieval by the end user community. Finally, an easy-to-use browser-based interface needed to be explored that will make it convenient for users to accomplish the task of searching with relevance. Documents stored face the challenges of historic data growth, which need to be addressed.

Computer science has offered technologies that have been time tested and are available via the Open Source community. The Department of Defense (DoD) also has software vendor licenses that can be leveraged to study solutions. A hybrid approach seemed to be fit for the exploratory nature of this project. With the resurgence of Artificial Intelligence and Machine Learning (AI/ML), algorithms were looked at that might automate the process. Optical Character Recognition (OCR) techniques were explored, which are the first step in storing the files in a database. User interfaces that work with a browser seemed common enough, and those which use technologies like HTML5, JavaScript and Apache-Tomcat webserver were studied.

Findings and Conclusions
NECC commands receive reports in formats of PDF, Microsoft Word and PowerPoint that are abstracted from the processing of the raw data. The abstracting makes it easier for the community to make sense of the findings; thus, the project’s focus was narrowed down to document processing as opposed to raw file processing. The documents fit into the commonly known type; thus, existing Python libraries were available to process them, as opposed to the need for developing custom code.

Since preprocessing of the raw data removed extraneous content, the document sizes were not in the Big Data range. This made it unnecessary to consider HDFS. Instead, a database (vendor Oracle) was able to meet the storage (and data growth) requirements.

A Python library was used to convert different document types to an image, and OCR on the image was done using the Tesseract library. A trained algorithm that recognized page orientations finally prepared a list of words from the image. The images with the OCR were stored in the database.

When end users searched for documents using keywords, the Python libraries implementing the cosine similarity algorithm were used to develop metrics to determine closeness of the document (to the keywords). The metadata was saved in a database table for future access.
Finally, the user interface was linked to the Apache webserver and the Oracle database using the FLASK framework and the Python programming language.

While there are many AI/ML algorithms, the ones related to the cosine similarity algorithms were the focus.

**Recommendations for Further Research**

The current architecture is presented as a recommendation which can be taken into an implementable model. The model could be based on a local machine or a networked Cloud option. For the long term, a secure DoD Cloud solution will make it easy for the community to search, using a wide range of keywords. Separate DoN commands can then decide what information serves them the best. A parallel version can exist in the classified domain.

In this study, only preprocessed documents were considered. A follow-up study will look at raw data and custom techniques to make sense out of the information. This will involve an evaluation of many more technologies.

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**NPS-21-N186-A: Subseasonal to Seasonal (S2S) Forecasting of Tropical Cyclones**

**Researcher:** Dr. Tom Murphree  
**Student Participation:** No students participated in this research project.

**Project Summary**

Tropical cyclones (TCs) can have major impacts on planning and executing national security operations. For operational planning, it is important to forecast TCs at subseasonal to seasonal (S2S) lead times. However, existing TC forecasting systems have limited skill at these leads, limited spatial and temporal resolution, and limited information about forecast uncertainty and confidence. These limitations make existing forecasts problematic for operational use. To address these limitations, we designed and tested a hybrid version of two existing forecasting systems. The hybrid system uses a statistical model to process the outputs from a dynamical model and generate probabilistic forecasts of TC formation at leads out to 90 days and with resolutions of one degree and one month. The forecasts provide quantitative information about the spatial and temporal variations in the probabilities of TC formation, as well as information about forecast uncertainties and forecaster confidence. The statistical model was trained on ten years of forecasts from the dynamical model. We did hindcast testing of the hybrid system based on all the years used in the statistical model development and then applied that model to forecast 2021. We developed two versions of the hybrid system, one for the western North Pacific and one for the North Atlantic. Both the hindcasts and the forecast show high skill for each of the two regions. We found that our hybrid approach can substantially improve the outputs from existing operational forecast systems. This finding is supported by feedback that we received from two operational centers (Joint Typhoon Warning Center and the Climate Prediction Center) that have used our forecasts in developing their operational products. We recommend that our results be extended to address (a) additional regions, lead times, and valid periods; (b) TC track forecasting; and (c) TC intensity forecasting.
**Keywords:** tropical cyclones, TCs, operational planning, western North Pacific, North Atlantic, meteorology, oceanography, climate, subseasonal to seasonal, S2S, forecasting, dynamical-statistical forecasting, Navy, national security, Earth System Prediction Capability, ESPC, Climate Forecast System Version 2, CFSV2, Joint Typhoon Warning Center, JTWC, National Centers for Environmental Prediction, NCEP, Climate Prediction Center

**Background**

Tropical cyclones (TCs) can cause major disruptions of many types of operations and can also present opportunities for other types of operations. This applies to US Navy operations in most regions of the world, but especially in the western North Pacific, North Atlantic, and Indian Ocean regions, where the Navy is active and where TC activity levels are high. Thus, skillful forecasting of TCs is essential to Navy planning and decision making. However, there are very limited options for Navy planners seeking TC activity forecasts at subseasonal to seasonal (S2S) or longer lead times. Most existing S2S TC activity forecasts have limited spatial and/or temporal resolution, and limited skill, especially at leads greater than one to two weeks.

The Naval Postgraduate School (NPS) long lead TC forecasting system is an example of a skillful and relatively high resolution S2S TC formation forecasting system. This system is used operationally to support S2S forecasting by the National Oceanic and Atmospheric Administration (NOAA)Climate Prediction Center (CPC) and Joint Typhoon Warning Center (JTWC). However, potential improvements to the system need to be investigated. These include upgrades to (a) the training data sets used to develop the statistical model component of the system and (b) the dynamical model component of the system. In this project, we assessed the potential to make these improvements using recently upgraded and new versions of the training data sets and dynamical models, including the Navy Earth System Prediction Capability (ESPC) dynamical prediction system.

Our main objectives were to assess the potential of
1. New data sets to improve the resolution and accuracy of the NPS system statistical models
2. New dynamical inputs to increase the forecast lead times and skill.

Our main questions were
1. How can statistical models of the relationships between TC activity and large-scale environmental factors be improved by the use of new environmental data sets?
2. How can the forcing of the statistical models be improved by the use of new S2S dynamical forecasting systems?
3. What are the improvements in the lead times, skill, and operational value of S2S forecasts of TCs that are derived from the revised statistical models and dynamical forcing of those models?

Our main tasks were to
1. Revise the NPS system using new / upgraded data sets and dynamical system inputs.
2. Assess the revised system by conducting and verifying multi-year hindcasts and current-year forecasts.
3. Assess the potential of new / upgraded data sets to improve the resolution and accuracy of the statistical components of the system.
4. Assess the potential of inputs from the dynamical system to increase the lead times and skill of the NPS system when those inputs are used to force the revised statistical component of the NPS system.
5. Work with forecast users to assess the forecasts and the potential operational applications of the forecasting system.

**Findings and Conclusions**

We found that substantial improvements in the skill and operational value of TC formation forecasts can be achieved using a dynamical-statistical hybrid approach in which

1. The statistical model is trained on an extensive set of (a) TC formation data and (b) forecasts from the dynamical model that represent the biases of the dynamical model.
2. The predictors used by the statistical model (a) are dynamically related to TC formation, (b) have statistically significant relationships to TC formation, and (c) have a high degree of statistical independence from each other.
3. The forecasts from the dynamical model used in the training (a) span at least the most recent ten years, (b) provide forecasts of predictors that have the properties stated in item 2 above, and (c) are based on the dynamical model that is used to produce real time forecasts.

We also found that

1. The NOAA Climate Forecast System Version 2 (CFSV2) meets the criteria in item 3 a-c above. Thus, we used CFSV2 forecasts in this study.
2. The Navy ESPC system does not yet provide an archive of forecasts that meet the criteria stated in item 3 a-c above. Thus, we determined that this system is not yet ready for use in a hybrid dynamical-statistical approach.
3. The separation of the forecast probabilities into three probability categories that represent 50% of formations, 70% of formations, and 90% of formations provided forecasts that were more quantitative, understandable, and operationally useful.
4. The skill of the hindcasts and forecasts from the hybrid system is positive at all leads.
5. The skill of the system was dramatically improved when the training data for the statistical model were archived CFSV2 forecasts rather than reanalyses.
6. The skill of the one-, two-, and three-month lead forecasts is similar, with modest declines in skill with increasing lead time. This indicates that there may be skill in forecasts at leads longer than three months.
7. The forecasts from the hybrid system are unique in several ways, especially in terms of spatial and temporal resolutions, their use of area probabilities to predict point locations, and the categorical probabilistic information. To address these unique features, we developed new metrics to assess forecast skill. These include metrics for (a) the percent of the TC basin for which elevated formation probabilities were predicted and (b) the number of formations that were successfully predicted per unit area.
8. Skillful S2S forecasts of TC formation lay the foundation for skillful S2S forecasts of TC tracks and intensities.
9. We recommend that N2/N6 support additional operational testing in partnership with JTWC, CPC, and their customers to increase the understandability and operational value of the forecasts. Presentation of our research to these partners and customers is an important next step (Meyers et al., 2021).
Recommendations for Further Research
We recommend that additional research be conducted to address
1. Additional tropical cyclone (TC) activity and national security operations (e.g., in the northern Indian Ocean)
2. Additional lead times (e.g., one- to two-weeks, four- to five-months)
3. Additional valid periods (e.g., one-week to three-week periods)
4. Hybrid methods for subseasonal to seasonal prediction of TC tracks and TC intensity
5. The transitioning of hybrid forecasting systems to operational use
6. Methods for improving the understandability and operation value of the system forecasts, especially in the planning of national security operations.

References

NPS-21-N260-A: Machine Learning (ML) for Signal Detection

Researchers: Dr. Frank Kragh and Ms. Donna Miller
Student Participation: LCDR Bart Ellison USN

Project Summary
Often, United States reconnaissance systems collect a very large amount of data that must be sorted into the data useful to the mission (signals of interest [SOI]) and the rest of the data. Often, the SOIs represent a small portion of the large data set. It is important to effective warfighting to find these SOIs quickly and with high probability of success. Usually, not enough manpower or manhours are available to do this task manually. Automatic techniques are required. In this research, we use a type of neural network to enable a machine to learn how to discriminate between SOIs and other signals. This machine learning method successfully performed the discrimination using our synthetically generated radio signal data set. We conclude that this method is valuable to the sorting task, and therefore to warfighting, and should be examined further to determine if it is as successful on fully realistic radio signals.

Keywords: signals intelligence, SIGINT, communications intelligence, COMINT, neural networks, machine learning, ML, generative adversarial networks, radio communications

Background
The radio signals of an adversary, often called SOIs, provide an opportunity for gathering information known as communications intelligence (COMINT). American forces use various methods and systems to collect radio signals, resulting in large collection sets of digitally recorded radio signals, often including all radio signals in a wide frequency band transmitted over a large geographic area. It is important to quickly and efficiently identify adversarial SOIs from the often much larger collection of signals. The raw communications data collected for analysis is typically a huge amount of data, generally too large for
human analysts to search through the communications signals to find the adversarial SOIs for further study. Furthermore, collected signals are often stored as raw down-converted, but not demodulated, in-phase and quadrature discrete-time samples, sometimes called pre-demodulated. The growth of wireless technologies over the past several decades has greatly expanded the density of signals present within the radio frequency spectrum, compounding this sorting problem. This has intensified the need for automatic computer-based techniques for quickly sorting through large collections of pre-demodulated communications signals. Automatic search methods can help put the SOIs that the warfighters need in their hands more quickly, enhancing their effectiveness.

Generative adversarial networks (GANs) are a specific configuration of two neural networks, called the generator and the discriminator, first discussed in the literature in 2014 (Goodfellow et al., 2014). Most of the use of GANs has been associated with images, with very few applications involving radio signals. Our research group continues to expand the applications of GANs to radio signals. In other work, we have shown that GANs can be used with great effect in analyzing channel-induced distortions on a signal (Germain & Kragh, 2020, 2021a, 2021b). Herein, we use GANs to analyze the message information in radio signals, which we believe is a first. This shows promise for being able to ascertain the message information in radio signals without traditional demodulation. While that remains a yet-to-be-achieved goal and distinct from our goals in this research, that would allow the determination of the message without knowing the modulation scheme, which would have great application to signals intelligence, adaptive radio technologies, and other communications engineering endeavors.

The data used in this research were four sets of computer-generated, quadrature phase-shift keying signals. Two sets were not SOIs, some labeled and some unlabeled. The other two sets were SOIs, some labeled and some unlabeled. The GAN was trained data using some data from each set with the GAN aware of the labels, when present. The GAN learns the statistical distinctions between SOIs and the others, and the discriminator calculates a probability that each signal is an SOI. When the GAN learns sufficiently well that the discriminator calculates probabilities near one for each SOI and near zero for each non-SOI, for even those unlabeled, the GAN is sufficiently trained. Thenceforth, the discriminator can be used to classify unknown signals as likely or not likely to be an SOI.

Findings and Conclusions
The semi-supervised generative adversarial network (SGAN) was able to classify signals within a dataset consisting of a single modulation type using only pre-demodulated data. The SGAN performed exceptionally well at classifying these signals. The research showed minimal difference in the performance of the SGAN when using 25%, 50%, or 75% of the dataset for training, which is good. Other forms of neural networks require more training. The most significant factor in SGAN classifier performance was the length of the snippets. Using the snippets of length, 256 discrete-time samples outperformed training using either the snippets of length 128 or 512 discrete-time samples. Regardless of the training dataset size and snippet length, the SGANs performed almost identically at each signal-power-to-noise-power ratio (SNR). All of the SGAN classifiers were at or above 99% accurate at SNRs of 0 decibel and greater. This performance was exceptionally high and we view it as a success. A more varied dataset, incorporating variations expected at a typical receiver, including multipath channel distortions and initial unknown phase, could affect the accuracy. Training time for the single modulation SGANs varied greatly as the dataset size and length of the snippets increased. SGAN 3, the most successful configuration, using the 256 discrete-time sample length, required about 4.5 minutes to train using 25% of the dataset.
Overall, the SGAN was able to classify signals within a single modulation scheme as SOI or non-SOI with great accuracy with modest training time.

Our research shows promise, and we believe we are the first to apply GANs to signal sorting within a single modulation scheme. We recommend more work be done to ensure the original goals are met. Specifically, it is important to confirm these results are repeatable with a dataset that includes typical multipath channel distortions and other realistic effects which are expected in typical signal collections. Our new understanding of these automated SGAN-based processes will allow accurate automatic identification of SOIs in a timely manner, identifying more SOIs and saving time as compared to manual identification of SOIs, achieving the original goals.

**Recommendations for Further Research**

This research has shown that the semi-supervised generative adversarial network (SGAN) has the ability to identify signals of interest (SOIs) within a large set of signals. The SGAN architecture showed great promise as a way to train a neural network to identify an SOI.

One potential area of future research would be to explore a different architecture such as an Auxiliary Classifier-GAN or an improvement on the existing SGAN by adding more neural layers, perhaps yielding even faster training. A second area for future research would be to experiment with an early stop-training feature when the accuracy has stopped improving, thereby decreasing training times. Third, the amount of training data required could be explored. At our smallest size, we used 25% of the dataset to train the SGAN. The performance of the classifiers indicates that the amount of the dataset used to train could be even lower, likely resulting in faster training. Fourth, the signal dataset could be enhanced to make the classification more realistic, and perhaps, challenging. The dataset used only white Gaussian noise as an impairment. More impairments such as center frequency offset, random initial phase, sample rate jitter, and multipath fading could be added to the dataset. Over-the-air signals could be collected to create a more realistic dataset. Another dataset using a more complicated modulation scheme could also be created to test the limits of the SGAN’s ability to classify signals. While all of these four recommendations would explore important issues, the last one seems to us the most important to improve the likelihood that a deployable solution could be developed and used successfully.

**References**


NPS-21-N342-A: Battle Management Aids: Leveraging Artificial Intelligence for Tactical Decisions

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Project Summary
The development of artificial intelligence (AI) capabilities has the potential to transform the traditional battlespace. Advances in computational technologies and AI methods present new opportunities for developing automated battle management aids (BMAs) to support a variety of warfighter missions. Tactical decisions have become increasingly complex and can overwhelm human decision-making as threats increase in number, speed, diversity, and lethality. Peer competitor nations are also developing intelligent systems to enhance their situational awareness and decision-making. To maintain decision superiority in the battlespace, the Navy must leverage AI for improving situational awareness, for developing decision options and dynamic plans, and to predict the consequences of military courses of action (COAs). This study developed conceptual designs of AI-enabled BMAs for several tactical and planning mission domains and demonstrated the use of machine learning (ML) for several decision aid applications.

The research investigated the following five areas: 1) AI and advanced data analytic methods and mapping specific methods to the air and missile defense kill chain functions; 2) human-machine trust between human warfighters and conceptual AI-enabled BMAs for air and missile defense; 3) the cognitive laser concept—the use of AI-enabled BMAs as decision aids for operating laser weapon systems; 4) the use of automated methods and AI to improve naval aviation planning systems; and 5) the use of AI and ML for an automated system to detect cyber-attacks on the Global Positioning System (GPS).

The study’s primary outcomes are that AI-enabled BMAs are necessary to address the growing complexity of warfare, they have applications in a variety of military domains, and by leveraging AI and advanced data analytical methods they are central to ensuring future naval warfare superiority.

Keywords: artificial intelligence, AI, machine learning, ML, battle management aids, BMA, human-machine teaming, automated decision aids, weapons engagements, mission planning, human-machine trust, air and missile defense, cognitive laser, laser weapon system, systems engineering, tactical warfare, naval aviation, Global Positioning System, GPS

Background
The goal of AI is to create systems that can function intelligently and independently. In broad terms, AI encompasses the computer processing of images using symbolic learning to enhance what is “seen,” and the processing of data using ML for speech, object, and pattern recognitions as well as cognitive learning
and analysis for classification and prediction. Advances in sensors, communications, big data, and computers offer a prime opportunity for AI solutions. With large amounts of data from different sources and increased processing speeds, AI methods can provide the means to greatly improve tactical knowledge and COA decisions.

AI-enabled applications, such as automated decision aids for tactical missions (Johnson, 2019) and predictive analytics and game theory for mission planning (Johnson, 2020; Zhao & Nagy, 2020), offer huge gains in naval decision effectiveness and tactical superiority. The speed of warfare today often exceeds the cognitive abilities of humans to make decisions (Galdorisi, 2019). The Navy has acknowledged the need for AI and ML to support warfighters. Naval warfighters need real-time decision aids to support human-machine teaming for complex decisions that enhance human cognitive abilities with fast and robust computational prowess.

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

The study developed conceptual designs of AI-enabled BMAs for several different tactical and planning mission domains: air and missile defense, shipboard counter-unmanned aerial system (C-UAS) defense using laser weapon systems (LWS), naval aviation planning, and cyber defense of the GPS. The study demonstrated the use of ML for three BMA applications: (1) for determining the LWS dwell time required to burn through a threat target based on the target's material characteristics and thickness, (2) for selecting the best LWS engagement strategy for countering a UAS swarm threat, and (3) for detecting a cyber spoofing attempt on GPS.

This study applied a systems analysis approach to understand the problem space and to develop engineered solution concepts. The study collected data and information through a literature review, participation in virtual conferences and workshops, and discussions with subject matter experts. The study developed system artifacts including requirements, context diagrams, system views, operational views, functional analysis, and conceptual design for BMAs in several mission domains: air and missile defense, laser weapon system operation, naval aviation planning, and a system for GPS cyber protection. The study researched human-machine teaming concepts and developed an engineering framework for developing trusted AI systems. The study developed machine learning algorithms using a combination of simulated and operational datasets for proof-of-concept analysis. The study researched AI methods and mapped specific methods to specific functions in the kill chain. The study included a Naval Postgraduate School research team as well as two capstone teams and six thesis students.

Findings and Conclusions
The study’s primary outcomes are that AI-enabled BMAs are necessary to address the growing complexity of warfare, they have applications in a variety of military domains, and by leveraging AI and advanced data analytical methods they are central to ensuring future naval warfare superiority. Findings in each of the five research initiatives follow.
The first research initiative mapped AI methods to the tactical kill chain. A team of capstone students studied AI methods including ML, predictive analytics, statistical data analytics, wargaming strategies, and game theory methods to understand the capabilities and limitations of these methods. The team then studied tactical kill chain functions and decisions for the air and missile mission domain. The team mapped the AI methods to the kill chain functions. They determined that AI can enhance the kill chain, address battlespace uncertainty, and provide effective COA options in complex threat environments.

The second research initiative studied human-machine teaming with a focus on achieving an effective trust relationship between operators and future AI-enabled BMAs. Appropriate trust must be established and maintained between human operators and BMAs for effective human-machine teaming. This study reviewed trust definitions, human-machine interactions, conceptual models of BMAs for air and missile defense, threat scenarios, and functions. The study developed an engineering framework for developing and implementing future AI-enabled BMAs that achieve calibrated trust between human operators and the AI system. The framework should focus on three areas: (1) collective and individual human’s perception of automation technology and AI-enabled BMA, (2) enhancing human-machine teaming dynamics, and (3) achieving trustworthiness of the AI-enabled BMA during system design and development.

The third research initiative was the cognitive laser—a proposed AI-enabled BMA to support the operation of LWS. This study developed requirements, concepts of operation, and a conceptual design for the cognitive laser. The study researched an integrated kill chain approach for shipboard LWS with kinetic weapon systems and engagement strategies for C-UAS swarm threats. Study results indicated the need for a cognitive laser approach for future LWS and demonstrated the utility of ML for LWS tactical decisions.

The fourth research initiative studied naval aviation mission planning. This study identified issues with the current aviation planning system. These issues stem from the manual nature of the system and result in an overly long time required to develop aviation plans, inability for dynamic replanning, and problems with effective aviation missions. This study proposed the use of automation to develop a future naval aviation mission planning system that addresses the limitations and issues with the current system.

The fifth research initiative studied GPS cyber-attacks and demonstrated a method for detecting GPS spoofing attempts using ML. This study developed training datasets using operational GPS data and simulations of GPS spoofing attempts. The study trained ML algorithms using the datasets and then evaluated the ML system’s ability to detect GPS spoofing. The study demonstrated the efficacy of this approach, which provides supporting evidence for the use of AI-enabled BMAs for a variety of military applications.

Recommendations for Further Research
This study recommends continued research in five focus areas: developing artificial intelligence (AI) methods for the tactical kill chain, human-machine teaming for AI-enabled battle management aids (BMAs), the cognitive laser, the future naval aviation mission planning system, and the use of AI for defense against cyber-attacks in critical systems.
The first focus area for future research is on the design and development of specific AI methods for implementation in future tactical kill chains. Initial findings from this study show that different AI methods will be needed for the different functions in the kill chain and that a more complex mapping will be required rather than a simple one-to-one mapping. It is likely that a federated learning approach will be required that orchestrates a heterogeneous set of machine learning (ML) algorithms and AI methods that can handle the highly complex spatial-temporal dynamics of a tactical battle scenario. A significant level of research is required to identify and evaluate different and novel AI algorithms and methods for this application.

The second future research area is human-machine teaming. This study focused on the trust relationship between human operators and future AI-enabled BMAs. The study recommends developing an understanding of the true capabilities and limitations of future AI-enabled BMAs, increasing training requirements to cope with a new job scope and evolving threats, and ensuring AI system developments include requirements for trustworthiness. Additional research is required to study many other aspects of human-machine teaming including explainability, useability, human factors, human-machine interdependency, cognitive loading, and adaptive and agile levels of autonomy.

The third area of future research is the cognitive laser. Additional research is needed to apply AI methods to the laser weapon system (LWS) kill chain and to integrate the LWS kill chain with other defensive systems they will collaborate with.

The fourth area of future research is the naval aviation planning system. Future mission planning systems need to leverage automation and AI methods to overcome current limitations and to support rapid planning, effective planning, and dynamic replanning to address future complex missions.

The fifth area of future research is in the use of AI methods for protecting critical systems, like the Global Positioning System (GPS), against cyber-attacks. This study demonstrated how ML can be used to detect GPS spoofing attempts. Continued research is needed to operationalize this application and study other mission domains where AI and ML can be applied.

References
NPS-21-N372-A: DMO Tactical Grid – Edge Processing, Mission Analytics, Officer Qualification

See: NPS-21-J087-A: DMO Tactical Grid – Edge Processing, Mission Analytics, Officer Qualification

NPS-21-N373-A: Business Intelligence for Expeditionary Advanced Base Operations (EABO) Shaping Flexible C2 Organizational Structure

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**Project Summary**  
The U.S. maritime operations, particularly in the littorals, have been contested and dangerous. It is imperative to apply advanced analytics to help operational or tactical units execute distributed maritime operations (DMO) and expeditionary advanced base operations (EABO). The DMO and EABO concepts require flexible configurations and combinations of capabilities and tactics across multiple domains to win in complex contested environments. The DMO and EABO concepts also require use of advanced detection and counter-detection technologies.

Distributed and collaborative computing and networking have been associated with peer-to-peer models. The researcher applies the peer-to-peer and self-organizing collaborative learning agents (CLAs) to meet the requirements of DMO and EABO. As an example of EABO, the researcher shows a use case for distributed Marine transportation units to handle transportation movement requests (TMRs). The researcher shows how to data-mine historical data, discover capability and behavior patterns, then apply them to design new peer groups to balance the load and maintain much lower signatures.

The researcher maps the need of lowering operation signatures to a load balancing problem and applies lexical link analysis (LLA) for CLAs. The researcher further applies the principle of quantum entanglement and superposition into a framework of LLA quantum intelligence game (LLAQIG). LLAQIG helps a peer simultaneously achieve the Nash Equilibrium for itself and the optimal total social welfare for its peer-to-peer network.

The LLAQIG is used to find the intrinsic value of a unit (i.e., a unit possesses a requested capability and has the potential to become a high-value unit). The LLA groups and LLAQIG quantum effect impact factor help a peer-to-peer network self-organize its units and make them appear more randomly connected, which therefore lowers signatures and avoids detection. The Department of Defense (DOD) operational or tactical units can potentially leverage the results for shaping flexible command and control (C2), organizational structures, and modernization.
Keywords: *business intelligence, expeditionary advanced base operations, EABO, collaborative learning agents, CLA, peer-to-peer systems, load balancing, lexical link analysis, LLA, quantum intelligence game, counter-detection, distributed operations, transportation capacity planning tool*

**Background**

The U.S. DOD, which has realized the importance of distributed operations, has conducted research as part of the modern warfare strategy (Priebe et al., 2019; Lundquist, 2021). The DOD resources have gradually migrated to large, distributed, more mobile and wireless networks of networks. However, the U.S. DOD faces very sophisticated adversaries and has to operate in contested, degraded, and dangerous environments.

Contested environments are degraded environments caused by enemy action, for example, laser, direct weapons, electronic warfare threats, and cyber attacks (Bell & Rogers, 2014). Degraded environments may also be caused by failed systems or battle damage. The warfare resource, capability, and assets of the U.S. DOD components may reside in different warfare domains such as sensors, platforms, networks, logistics, and weapons. Operational domains can also include different areas such as air, surface, subsurface, land, and cyber. Flexible C2 and organizational structures in terms of distributed combinations of the capabilities and tactics can provide plug-and-play maneuvers and multiple capabilities that are unpredictable by the adversaries.

To enhance total force readiness and project combat power in the contested environment, the U.S. Navy and U.S. Marine Corps (USMC) need offensive power of individual platforms through networked firing capability over a wide geographic area (i.e., larger hybrid fleet, consisting of manned and unmanned platforms and also the composition of the fleet and the right mix of platforms; Popa et al., 2018). This capability would deliver synchronized lethal and nonlethal effects across all domains including distributed weapons of increasing range and lethality (Navy Warfare Development Command, 2017; Lundquist, 2021). DMOs for a USMC EABO operation are essential concepts to maintain C2 superiority (Colpo, 2016) to conduct enduring sea control and power projection missions.

The DMO and EABO requirements need the state-of-the-art peer-to-peer system capabilities to manage capabilities, manpower, maintenance, and supply among distributed units using the right data strategy, distributed infrastructure, and deep analytics including business intelligence, artificial intelligence, machine learning, optimization and game theory (Zhao, 2021).

The researcher studied a use case: the Transportation Capacity Planning Tool (Tactical Edge, 2021), which is a centralized client-server system integrated with the Global Combat Support System-Marine Corps as a “bridge technology” used by the USMC to provide near-term transportation planning, management, and execution capabilities to supply operating forces. As a web-based application, it enables assets visibility and in-transit visibility that contributes important information to the logistical picture. The sample data contains 37,449 TMRs from 01-OCT-20 to 25-MAR-21 for 287 units and 15 pieces of equipment. The capabilities of a unit are associated with the equipment it operates.

The researcher applied CLAs and LLAQIG for the use case. The researcher used a single CLA to represent the data set from the centralized model to discover patterns of units’ collaboration and prioritize the units based on the capabilities (e.g., equipment) and characteristics of the requests (e.g., people or cargo), then
applied the data mining results to design peer-to-peer networks, whose goals are to self-organize, load balance, avoid being detected and targeted, and shape flexible C2.

Findings and Conclusions
The research found that it is important for DMO and EABO systems to foresee low load units with relevant capabilities and thus to select the units to balance the load and avoid being detected and targeted in a contested environment. The type of load balancing needs self-organizing techniques to guide a peer-to-peer system to converge to a desired topology. It is also important to index and match content and a service request.

CLAs include distributed, networked, and peer-to-peer agent architecture and analytics. A single agent ingests local data, indexes, catalogs them, and separates patterns and anomalies. Multiple CLAs work collaboratively using peer lists. CLAs employ unsupervised LLA that can be set as a LLAQIG (Zhao, Mata, & Zhou, 2021).

The researcher found that each unit or node can be represented as a single CLA. A unit can be a capability supplier, consumer, or broker. Each unit first builds a content and peer network to index, data-mine, and fuse data locally and from its peer network. When a unit receives a new request of capabilities, the unit searches its peer network for the best match to fulfill the request; meanwhile, it balances the load to lower the signatures and avoid detection.

Result #1: The data mining results show the top 26% (75 units) have 80% of all the workload (i.e., number of transactions). These units have higher loads than others, so they may be detected and targeted by the adversaries.

Result #2: The LLA groups have the following characteristics:
- Units in each group are peers of each other, sharing data and local indexes.
- Units in each group can search and match each other’s content (e.g., capability and characteristics patterns) for a new input of capability request (e.g., a specific equipment request).
- For a capability request entered to a unit of high load, the unit searches the peer network and finds the units that have low load and are linked to the requested capability. Consequently, the high-load units’ loads are routed and balanced to the low-load ones.
- After all the peer-to-peer networks are established from the LLA groups, the load in each group balances towards the average within each group.
- After such balancing (i.e., if each unit had the group average as a new load), then, as shown in the use case, 63% (182 out of 287) of the units would cover 80% of the total load. In a total random and load-balanced peer-to-peer network, 80% of the units would cover 80% of the total load. It is not possible to reach the total random configurations.

The LLAQIG quantum effect impact factor is used to show how likely a unit can adjust its load to an equilibrium one (e.g., a group average). The higher the LLAQIG quantum effect impact factor associated with a unit, the more likely its load can be balanced towards the group average. The social welfare of a whole peer system is optimized while a peer’s individual value is optimized as well.
Recommendations for Further Research

The researcher recommends working with the Transportation Capacity Planning Tool stakeholders to design new peer groups to distribute the capabilities and load as evenly as possible for better counter-detection based on Results #1 and #2.

In Result #1, patterns and lexical link analysis quantum intelligence game (LLAQIG) quantum effect impact factors can significantly lower the signatures. This strategy allows each unit in each group to connect to peers in other groups. There are no peer connections within the lexical link analysis (LLA) groups. The number of capabilities is relatively similar in each new peer group. New peer groups can perform similar service requests. Furthermore, 74% (213 out of 287) of the units count for 80% of the total load. The LLAQIG quantum effect impact factors are used to make each peer group appear more even and random, lowering signatures inherited from the original centralized environment.

Future work is needed to validate the methodologies to different domains of distributed operations. For example, two data sets are identified for future work:

#1: The methods of transportation are managed by Tanker Airlift Control Center. The data set (Anderson, personal communication, 2021) includes 30 days of daily data of 1075 aircrafts which performed Department of Defense missions from worldwide locations and from 5/22/2021 to 6/20/2021. The data set includes 86 variables and 44 are selected for the analysis including daily mission capable and non-mission capable time (which require maintenance), where to start and land, end of day locations, mission codes, etc., totaling 32,167 records. Collaborative learning agents (CLAs) and LLAQIG can potentially use the patterns discovered from the big historical data to optimize the large-scale selection and routing of the airlift and channel operations.

#2: A data set related to the distributed maritime operations (DMO) concept: Navy’s warfare resource, capability, and assets may reside in different traditional warfare domains such as sensors, platforms, networks, and weapons, as well as the new tactics related to the DMO concept. An order of battle incorporates maritime platforms of surface ships, aircraft, weapons systems and sensors for both friendly and enemy forces. The high-level information of each platform and asset for this paper is compiled from open source databases, where a kill chain typically contains the three steps “find, target, and engage” (Joint Chiefs of Staff, 2013). A demand or operational node such as U.S. Fleet Forces C3F or C7F may require capabilities of unmanned aerial systems; intelligence, surveillance, and reconnaissance; electronic warfare; or new capabilities of handling gray zones (e.g., South China Sea). In the current command and control (C2) structure, a maritime operations center may communicate with a carrier strike group or an amphibious ready group, then a carrier task force. CLAs and LLAQIG can potentially show more flexible C2 structure to be re-organized in a more dynamic fashion and handle a vast amount and wide range of capabilities, resources, and requests through the integration of manned and unmanned systems, execution of deceptive tactics, and enabling units to conduct offensive strikes.
References


N3/N5 - Plans & Strategy

NPS-20-N084-A: Mitigating the Impact of China’s BRI on U.S. Interests and Access in the Indo-Pacific

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Project Summary
In this project, we assess the extent to which Chinese firms and the Chinese government have succeeded in using the Belt and Road Initiative (BRI) to gain control over ports in the Indo-Pacific and challenge U.S. security interests. The research team, which includes experts in China and the Indo-Pacific region, examined Chinese port activities in Southeast Asia, South Asia, and East Africa. The overall findings from this analysis are that after the burst of activity in the early 2000s led to Chinese control of ports in Djibouti, Pakistan, and Sri Lanka, China’s involvement in port-related projects has not grown rapidly, and contrary to the fears of many experts, China has not brought many more ports under control and has faced new obstacles in expanding its control of other ports. These findings suggest that the BRI provides limited leverage for Chinese actors that wish to expand their control over Indo-Pacific ports and establish logistics facilities to support Chinese military operations and challenge U.S. Navy access and operations.

Keywords: China, Belt and Road Initiative, One Belt One Road, ports

Background
In 2013, Chinese President Xi Jinping declared his intention to create a modern version of the ancient Silk Road that linked China to other parts of Asia as well as the Middle East and Europe. Now known as the Belt and Road Initiative (BRI), his vision has evolved into a foreign policy umbrella that encompasses nearly every aspect of China’s engagement with the world, including digital infrastructure, outer space, and health. At its core, the BRI features heavy investments in physical infrastructure. There is a voluminous literature on the BRI covering topics such as China’s motivations, the degree to which the BRI represents a coordinated strategy, and the building of railways and the expansion of China’s influence throughout Asia and the world. Building and controlling ports are an essential feature of the so-called Maritime Silk Road, but this aspect of the BRI has received less attention. Existing research and policy documents that briefly address ports increasingly view Chinese control over ports, especially in the Indo-Pacific region, as a severe threat to the security interests of the United States and its allies and partners, and a potential threat to U.S. Navy access and operations. This project fills a research gap and examines an issue of extreme importance to the U.S. military, especially the U.S. Navy.

Findings and Conclusions
In this project, we assess the extent to which China has succeeded in using the BRI to gain control over ports in the Indo-Pacific.
The research team included regional experts who examined Chinese ports in Southeast Asia, South Asia, and East Africa to identify patterns in each region and draw comparisons between the regions. We employed the comparative case study method and had each of the regional experts address a standard set of issues: Chinese interests in the region, the response of countries in the region to the BRI, and the full range of port projects that Chinese companies have pursued in each country. We relied on sources from China and the regional countries to create a catalogue of all the ports in these three regions and examine the potential for China to expand its control over more ports in the future.

We have three main findings. First, since the BRI was launched in 2013, China has not gained control over any large, integrated port projects in the Indo-Pacific apart from those in Djibouti, Gwadar, Colombo, and Hambantota. Chinese firms have engaged in finance and construction of new projects but have only acquired the right to operate a small number of ports or port terminals, usually in joint ventures with host-nation partners. This suggests that the BRI provides limited leverage for Chinese actors that wish to take control of Indo-Pacific ports and establish logistics facilities to support Chinese military operations. Second, domestic opposition is an important obstacle to widespread and rapid expansion of Chinese involvement in foreign ports. In nearly every country, competing political and economic interests have sought to negotiate, renegotiate, suspend, and even cancel projects that Chinese officials and companies promoted. Third, another key obstacle to Chinese control over foreign ports comes from international involvement or rivalry. Governments in these regions are aware of this rivalry and often seek to extract the most favorable deal by forcing Japanese and Chinese firms to compete against each other.

From these findings, we can highlight three key implications for U.S. security interests. First, we should recognize that even when Chinese leaders have ambitious plans to invest in ports and expand their military influence in the Indo-Pacific, progress is likely to be slow and uneven. Chinese projects have enjoyed the most stability in countries where governments face little opposition, but there are few countries where opposition can be ignored. Almost everywhere, projects may be adopted, renegotiated, stalled, canceled, and revived, sometimes suddenly. Second, because Chinese port operators are present in so few countries, there are numerous ports in a variety of 11 countries throughout the region that are free of Chinese control. Third, in nearly every country, there are extensive opportunities for the United States and its partners to shape the outcome of Chinese-supported port projects. Although most governments welcome Chinese financial and technical support for infrastructure development, they are quite willing to consider alternatives that are more closely aligned with their own interests and available on more favorable terms.

**Recommendations for Further Research**

These findings and implications lead us to offer the following recommendations for areas of future analytical focus and further research.

- Focus analytical attention on existing ports and port-related proposals, and be alert to political changes that may accelerate or slow the progress of proposed port projects. Entirely new projects are rare and proposed projects are rarely built quickly, but the status of existing projects can change suddenly, especially when elections or coups result in a change of government.
- Pay closest attention to ports that are operated by Chinese companies rather than those that are simply financed or constructed by Chinese firms, since port operators have the ability to control
access. And pay attention to port projects that involve Chinese port operators, not just Chinese banks and construction companies, since they are the ones most likely to exert control over a port.

- Continue to cultivate partnerships in places where Chinese companies have established a significant port presence. Outside of Cambodia, there is little sign that countries wish to exclude the United States entirely. Instead, many aim to benefit from the economic opportunities that China presents while continuing to engage in security cooperation with the United States and its partners. Other than Djibouti, no country has explicitly agreed to permit a Chinese military presence.

- Set requirements for future basing and logistics support with the understanding that Chinese companies may acquire contracts to operate a port or terminal used by the U.S. Navy. In addition, Chinese companies may build or operate related facilities, such as telecommunications networks, power supplies, and nearby industrial zones. Each of these may constrain U.S. Navy access, basing, and operations.

- Prepare for an environment in which Chinese naval and commercial vessels are present in more places, in larger numbers, and on a more persistent basis, but recognize that most major ports are not operated by Chinese companies and remain available for use on a commercial basis by the U.S. and other navies. Increasing Chinese access to ports will enable the People’s Liberation Army Navy to sustain operations throughout the region, but there are numerous ports on which the U.S. Navy can rely to sustain its own operations and compete effectively with Chinese forces.

NPS-20-N307-A: China’s Strategic Modernization in a Post-INF Treaty World

**Researcher:** Dr. Michael Glosny

**Student Participation:** No students participated in this research project.

**Project Summary**

This project examined the implications of the end of the Intermediate-Range Nuclear Forces Treaty (INF) for China’s nuclear modernization and U.S. interests in the Indo-Pacific. The methodological approach was to draw mostly on Chinese-language sources to provide new insights on China’s perceptions of a “post-INF world,” its concerns about potential U.S. actions, and the implications for China’s own modernization. Although this is a very recent development, the overall finding is that Chinese experts are facing up to the reality of the end of the INF Treaty and engaged in internal discussions over the threats and opportunities in such a world, which is consistent with a more mature nuclear power. In these discussions, Chinese experts pointed to future U.S. deployments of medium-range land-based missiles into the theater as a potential threat and also emphasized concerns about new technological developments that might occur now that the U.S. is no longer constrained. American experts should continue to follow this discussion in China to determine which actions are most likely to enhance deterrence without increasing the risk of unintended escalation and arms races.

**Keywords:** China, United States, nuclear, INF Treaty, U.S.-China relations, strategic stability
Background
The Intermediate-Range Nuclear Forces (INF) Treaty, signed between the United States and the Soviet Union in 1987, eliminated land-based missiles and missile launchers with ranges of 500-5500km and served as one the key pillars in managing U.S.-Russia strategic relations and a major breakthrough in arms control. In 2019, both the United States and Russia withdrew from the INF Treaty. Although most of the policy analysis and initial research focused on the implications of the end of the INF Treaty for Russia, the United States, and broader arms control, this development will likely have substantial implications for U.S.-China strategic relations and strategic stability in the Indo-Pacific as well. Although Russian violations of range limitations were the main reason the United States withdrew, some experts argued that China’s massive build-up of medium-range missiles as a non-signatory to the INF Treaty, gave China strategic advantages while the U.S. continued to be constrained. As the end of the INF Treaty marks one of the most important developments in the nuclear realm in recent years, this project examines China’s perceptions and understanding of the post-INF world, its concerns over potential American or Russian deployments or developments, and how this will impact China’s own strategic modernization. The previous American decision to withdraw from the Anti-Ballistic Missile (ABM) Treaty in 2002 and develop a more robust missile defense system represented another huge shift in the global nuclear environment and arms control. This affected China by potentially undermining its nuclear deterrent capability, and Chinese officials and experts were very critical of the U.S. decision, repeatedly emphasizing the need to return to the ABM Treaty and taking several years before accepting the new era and trying to adjust to it. As this is a very recent development, it is potentially interesting to compare China’s reactions to the end of these two treaties to better understand China’s nuclear thinking. As this is a very recent development, there has been very little rigorous academic research conducted on how this will affect China and the Indo-Pacific.

Developing a deeper understanding of Chinese perceptions of strategic developments in a post-INF world and how China is likely to adjust its strategic forces is vital to the planning requirements of N3/N5. The end of the INF Treaty has now provided the United States with the opportunity to deploy previously prohibited missiles in Asia and Europe, to better enhance deterrence and restrict options for U.S. adversaries. Deepening understanding of how China may perceive and respond to certain new actions, declarations, and force deployments will help enhance U.S. deterrence and protection of vital U.S. Navy interests, while trying to minimize the chances for inadvertent escalation.

Findings and Conclusions
This project employed a qualitative social science methodology and utilized existing social scientific theories of threat perception and strategic force postures. The main source material came from a thorough and systematic analysis of Chinese-language sources. In this research effort, I collected, examined, and analyzed Chinese-language books and articles published by military officers, government officials, scientists, government think-tank analysts, and university scholars. The outbreak of COVID made research travel impossible, but I was able to draw on meetings in China in 2019.

The main finding of this study is that unlike its reaction to the end of the ABM Treaty, Chinese experts are facing the reality of the post-INF Treaty and engaged in frank discussions about the implications for China’s security interests and regional stability. There are also four key findings on more specific issues and questions.
First, Chinese experts mostly blame the United States for the end of the INF Treaty and rarely fault the Russian violations. Moreover, even though Russia can now deploy medium-range missiles that are within range of China, no Chinese experts expressed concern that potential Russian deployments could threaten Chinese security interests.

Second, the overall view was that an unconstrained United States would likely develop new classes of missiles and seek to deploy them within range of China, representing a more complete threat to China. Chinese concerns include forward deployment of U.S. medium-range land forces to Japan, South Korea, Taiwan, other partners in Southeast Asia, and Guam. Others noted with concern that the U.S. would seek to develop more advanced hypersonic capability, adapt the technology from sea-based missiles and develop more land-based missiles, and more advanced experimental technologies now that it was no longer constrained by the treaty. Other than Guam, Chinese experts noted that the U.S. may face obstacles and opposition to such forward deployments, and expressed much greater concern at the likely spur to advanced technological developments.

Third, the impact on China’s own modernization was usually only made indirectly, so the end of the INF Treaty may not be an inflection point or key driver of Chinese modernization. However, Chinese experts put the end of the INF Treaty in a broader context of a worsening international nuclear environment, and suggested that China’s continuing modernization is a response to this changing environment. Some Chinese experts argued that the implications for China’s modernization will be influenced more by how the U.S. behaves and responds in a “post-INF world,” suggesting the potential for further action-reaction cycles of arms races.

Fourth, the Chinese are unwilling to enter into any U.S.-Russia-China arms control negotiations if the three are treated as equals, always citing the huge gap in nuclear capabilities, but these experts suggest some openness to broader discussions that include conventional, hypersonic, space, and cyber capabilities. The prospects for trilateral arms control which U.S. officials have called for appear bleak, especially if they are focused on nuclear issues and ask China to make the same commitments as the other stronger nuclear powers.

**Recommendations for Further Research**

As the end of the Intermediate-Range Nuclear Forces Treaty (INF) is a very recent development, there are many areas for future research, and experts should continue to track the evolution of the overall debate on the “post-INF world.” Although all types of research and analysis of Sino-American nuclear relations and the implications of the end of the INF Treaty are certainly welcome, I would recommend more focus on Chinese-language sources to deepen our understanding of the adversary’s perceptions and responses. There are a few areas I would strongly recommend for follow on research and analysis. First, research should continue to track the Chinese analysis of potential U.S. deployments and technological advances. Chinese experts have much more freedom to discuss U.S. nuclear policy and capabilities than their own, so this is likely to be an area of more robust discussion in China. We should pay attention both to which actions might be seen as enhancing U.S. deterrence, but also focus on areas of concern for potential escalation. Second, in the context of continued analysis of China’s strategic modernization, experts should try to isolate the specific role and contribution of the end of the INF Treaty in driving further modernization. In a “post-INF world,” experts should examine the new vulnerabilities that China sees in its own forces, as well as ways to exploit new technologies to threaten U.S. capabilities and interests.
Third, rather than calling for trilateral nuclear arms control negotiations on an equal playing field, experts should both track the types of comprehensive discussions China might be open to, and try to engage Chinese experts with specific proposals for topics and agendas of such discussions. Such efforts would need to start at the Track II, or unofficial level, but some of these insights should inform the official policy level discussions.

NPS-21-N177-B: Prospects for Deterrence, Escalation, Coercion and War in the Indo-Pacific (Continuation)

Researchers: Dr. James Russell, Dr. James J. Wirtz, Dr. Michael Malley, and Dr. Wade Huntley
Student Participation: No students participated in this research project.

Project Summary
The project finds that the Navy must develop a new set of assumptions to guide its approach to deterrence, coercion and escalation in this complex theater. Cold War–era assumptions about deterrence based on strategic nuclear weapons must be re-examined and re-cast to reflect the complexities of all-domain conflict in which it will be increasingly difficult to segregate the levels of war (strategic, operational, and tactical). Furthermore, this project finds that a number of uncertainties, stemming from the introduction of advanced weapons technologies by regional states into the strategic environment, must be addressed by the Navy as it plans for the future.

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

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

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

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

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

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

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

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

Recommendations for Further Research
A central finding of this study is that the Navy and the United States need much greater fidelity on the dynamics of deterrence across this vast region. Stated differently, there is much that the Navy doesn’t know about how deterrence does and/or doesn’t work, given the regional complexities that stem from its geopolitics. The findings for this report suggest that the Navy investigate how to further operationalize strategies of deterrence across the various and previously referenced domains of conflict. This can be done through a series of table-top exercises and/or visits of research teams to key friends and allies across the AOR to establish common understandings on these critical questions of deterrence, coercion, and potential escalation to all-out war across the region.
NPS-21-N265-A: Baltic and the Grey Zone: Challenge and Response of LCS basing

Researcher: Dr. Donald Abenheim

Student Participation: No students participated in this research project.

Project Summary
The strategic focus on enhanced forward presence of U.S. and allied forces in the Baltics must include forward stationed maritime forces to maintain alliance cohesion, to deter conflict, and to contribute to victory in battle. Warships configured to service in this geopolitical grey zone can restrain or defeat Vladimir Putin’s Russia and its allies. In an ongoing bilateral exchange between the Office of the Chief of Naval Operations (OPNAV) with the German Navy, discussion has examined the basing of a U.S. Navy (USN) littoral combat ship in German Baltic ports with strong host nation support. This study finds that a U.S. naval role in the Baltic via forward basing has great merit and should be considered in the many conflicting goals of defense policy, naval strategy, and fleet design. In this respect, the U.S. Navy should deploy an enduring forward regional maritime presence, not only with regular sailing of U.S. warships, but a continued and increased role in exercises and frequent patrols to reassure the classic and new Baltic allies, to engage the Baltic partners who are semi-allies, and to deter the Russian threat in its variety. Also, the deployment of a littoral combat ship (LCS) would give the USN a credible and tangible role in the forward defense of U.S. and allied interests in Central and Eastern Europe in the pivotal maritime domain made up of the Baltic and Black Seas. Finally, granted the offer of the Federal Republic of Germany to base an LCS in the Baltic port of Kiel, with its excellent maritime infrastructure, OPNAV should consider the possibility of opening negotiations with the German government to base an LCS on the Baltic while keeping fully in mind that this undertaking has implications well behind the hull of the warship and the perimeter of its possible future German Baltic base.

Keywords: U.S. Navy, littoral combat ship, Baltic Sea, Russian Federation Navy, fleet design, NATO enhanced forward presence, deterrence, war at sea, maritime grey zone, Russian strategy, Russian foreign policy, war in confined waters, alliance cohesion, allied burden sharing, German Navy, Baltic ports, North Stream II, stationing, great power conflict, U.S.–Russian relations, U.S.–German relations

Background
The Baltic has lately come into focus as a site of great power confrontation. All the same, this sea suffers from a relative lack of prominence in contemporary U.S. naval strategic writing relative to crisis and war. This problematic fact takes nothing away from its fundamental role as a potential site of conflict, especially in relation to the revival of Russian power and its impact on Baltic North Atlantic Treaty Organization (NATO) allies, which this paper is dedicated to on the levels of maritime strategy, alliance burden sharing, and fleet design.

Specifically, this study on an LCS in the Baltic supports the need for current OPNAV policy and strategy and the greater lethality of fleet posture in the face of maritime threats across the spectrum of conflict, which is dominated by the so-called grey zone and ever more dangerous great power conflict—including the Russian bid to force the United States out of Europe and render zones of influence as in the Cold War or the 19th century. A political-military inquiry into the contemporary maritime basing issue allows a more efficient and lethal fleet in conjunction with allies and partners should tension proceed to conflict.
and armed struggle at sea and the territories adjoining to the Baltic. This research sharpens the analysis of postures/policies with associated implications for and impacts on the United States, especially with an eye toward how Putin’s Russian Federation damages peace and security in Northern Europe and beyond. This study especially treats the possible roles and missions of an LCS in peacetime, crisis, and war in the many dimensions of policy, strategy, operations, and tactics as well as host nation civil-military relations and the politics and policy of forward deployed U.S. maritime forces.

The present work represents a maritime-focused analysis of the geopolitical and naval threats in Northern Europe to aid contemporary decision making and bilateral and alliance naval affairs amid growing crisis. This study capitalizes on the authors’ four decades of experience in host nation support basing issues in Europe and interprets a literature of mostly European origin on the Baltic, war at sea, and geopolitical conflict that is a secondary area of interest in the U.S. Navy.

The research employs interdisciplinary qualitative analysis common to advanced study of strategic affairs as found in graduate research policy programs of strategic studies, now applied to the requirements of defense and military professionals. The work includes a content analysis of relevant policy and strategy documents with a view to the needs of U.S. Navy Europe and U.S.-European Command policy formulation.

Findings and Conclusions
Based on the assessment of U.S. strategic interests and challenges in the Baltic and the strong offer of partnership with the German Navy, this study makes the following recommendations:

• The USN must seriously examine, together with the German Bundesmarine, the stationing of an LCS in Kiel, Germany as a means to meet the Russian grey zone maritime threat and as a means to meet and defeat threats at the appropriate level of escalation before they spiral out of control to higher levels of conflict.
• The USN should increase naval alliance cohesion and interoperability with allies and partners.
• The USN should engage German willingness to share the burden of stationing costs and to capitalize on excellent naval/maritime infrastructure in a leading Baltic port where the USN has often been a guest presence for a century and more.
• The USN should emphasize the role of the USN with allies and partners in collective defense in Northern Europe versus the present overemphasis on the ground and air domains of crisis, conflict, and war in this part of the globe. The possible stationing of the LCS is a means to encourage equitable burden sharing with the kind of bilateral and multilateral agreements on host nation support going back to the 1970s.

Recommendations for Further Research
The U.S. Navy should support further policy research on forward stationing of warships in the Baltic via open source strategic studies debate to improve decision making for fleet design, alliance cohesion, and the professional education of officers who serve in these conflicted waters of the grey zone to preserve deterrence and secure victory in combat.
NPS-21-N290-A: The Battle of the Atlantic/Arctic in the Present and Future: Policy, Strategy and Operational Aspects for Crisis and War

Researchers: Dr. Donald Abenheim and Dr. Carolyn Halladay

Student Participation: No students participated in this research project.

Project Summary
This qualitative research explains the issue areas as requested by the N51 and, more generally, the challenges facing the Navy in the face of the Russian area denial threat on a global scale. Specifically, this historically informed analysis examines the Battle of the Atlantic in World War II, especially the key factors of government, economy, society, and above all, the human element in war in its totality. It disrupts the customary, single-cause myths about technology and presents the record of the past in its complete dimension. Today, amid power conflict, this form of war has reasserted itself, especially in the waters adjoining major hostile powers. While the past is no guide to the present nor, surely, to the future, aspects of the Battle of the Atlantic have merit because the United States and its allies face a shared Russian adversary and because no one can exclude the chance in this globalized world that the Russian, Chinese, and other hostile maritime forces in whatever posture of subterfuge and clandestine operations might strike at U.S. and North Atlantic Treaty Organization (NATO) naval forces in the Atlantic and its adjoining waters. The strategic analysis community of the U.S. Navy must perfect yet more precise and effective methods to employ examples from the past better to reflect on the present and future—with due consideration of such aspects of naval war as found in civilian government, economy, industry, personnel, and the imponderable of resilience. Moving beyond an analysis solely of weapons and tactics, this study finds that the most important factors for strategic consideration are the psychological and political strategic aspects of great power war at sea, the role of surprise, lack of preparation, the need to go on the defensive, and the rigors of victory in the widest political sense.

Keywords: Battle of the Atlantic, maritime strategy, submarine, anti-submarine warfare, ASW, capital ships, grand strategy, North Atlantic Treaty Organization, NATO, Kriegsmarine, Arctic, human element, Royal Navy, merchant fleet, convoy, war at sea

Background
The key factors in the Battle of the Atlantic and, indeed, the present analysis are the element of men and women in combat as well as the effective organization of government, an economy on a total war footing, a society that surmounts the evil of class conflict, and the imponderable of will. Persons with a passing knowledge of war in the past often see World War II through a fuzzy perspective overemphasizing the Pacific campaign, which goes immediately from December 1941 until the climactic island campaigns of mid-1944. In fact, U.S. grand strategy and the maritime war from roughly 1938 onward assigned greater strategic importance to the Atlantic theater—and rightly so. While the past is no guide to the present nor, surely, to the future, aspects of the Battle of the Atlantic have merit in the face of today’s Russian adversary and the chance in this globalized world that the Russian, Chinese, and other hostile maritime forces in whatever posture of subterfuge and clandestine operations might strike at U.S. and NATO naval forces in the Atlantic and its adjoining waters.
The methodology for this historical study focuses on qualitative research by social scientists and historians in the Department of National Security Affairs at the Naval Postgraduate School as well as work by researchers at allied and partner civilian and naval institutions who have specialized in this theme. This qualitative research explores the issue areas as requested by the N51, particularly the challenges facing the Navy in the face of major war at sea between major naval powers.

The emphasis here falls on the opening phases of this historical campaign and especially on the stages in which the Axis offensive was manifest and the U.S. naval response was on the defensive—back when the outcome was hardly a given. The issues raised here are the classic ones of a.) offense and defense in war at sea; b.) the will and means of an aggressor to wield deadly blows on an opponent; and, in contrast, c.) the ability of the naval force at first on the defensive to go over to the offensive on the operational and strategic level.

More is to be found in this victory than the effortless sleight of hand technological “offsets” embraced by a small group of heroes generally in uniform and often just admirals against hapless Germans. The victory at sea was an expression of total and people’s war fought at sea on a global scale with exceptional violence and staggering cruelty to human life. This paper proceeds from both the Allied and Axis perspectives, with much attention paid to the latter. The mind and means of the aggressor are always elements to keep at the forefront of analysis, especially when the future demands a response by the naval strategic planner, but the imponderables of war and the confusion of the present cloud the effort at analysis and the weighing of ends and means.

**Findings and Conclusions**

Contemporary strategy faces several issues examined in this work: great power war; combat on a global scale; state of preparation for conflict and burdens placed on armed forces and national power to respond to strategic surprise; industrial base for ship building and innovations in armaments and naval organization; the role of personnel and casualties in combat; and finding the path to victory via ends and means of naval warfare. The examples of these issues in the past speak to makers of naval strategy today.

- The victory at sea in the Battle of the Atlantic was an expression of total and people’s war fought at sea on a global scale with exceptional violence and staggering cruelty to human life.
- A war in the Atlantic in a time to come, as well as the past war, both require a more prominent place in the professional military education, the training of young officers, and even the training of naval noncommissioned officers.
- War at sea is never a thing in itself, separate from other domains of warfare as it is called today. Nor is such war at sea separate from government, economy, and society.

Human nature in the vastness of time has altered but little, and military virtue is needed more in the 21st century than in other times because of the shrinking size of armed forces and the relative lack of direct experience of combat. An overemphasis on naval combat as an “engineering problem,” which loses sight of the political, social, economic, and human factors in war, faces a dim future in battle with an opponent that is not only ideologically motivated but is also better able to organize state, economy, and society to support war at sea (as well as in other domains).
Recommendations for Further Research
The U.S. Navy should build the capacity of young U.S. Navy strategists to have the highest familiarity with the record of war at sea on a large scale as it pertains to the factors of geopolitics, as well as the actual record of strategy versus legends and myths focused on the tactical level of such combat. The strategic analysis community of the U.S. Navy must perfect yet more precise and effective methods to employ examples from the past to better reflect on the present and future—with due consideration of such civil-military aspects of naval war as found in civilian government, economy, industry, personnel, and the imponderable of resilience. Such research as applied to the making of strategy must move beyond an analysis solely of weapons and tactics. Analysis must include the psychological and political strategic aspects of great power war at sea, the role of surprise, lack of preparation, the need to go on the defensive, and the rigors of victory in the widest political sense.

N4 - Fleet Readiness & Logistics

NPS-21-N014-A: COTS Microgrids for Sustainable Energy Integration and Resiliency

Researchers: Mr. Alan Howard, Mr. Brandon Naylor, Ms. Kristen Fletcher, and Ms. Michelle Hancock
Student Participation: No students participated in this research project.

Project Summary
This research effort examined the paths to further adoption of sustainable energy at coastal facilities. It examined current technical, financial, legal, and policy challenges that have hindered past efforts to incorporate more renewable energy and that are priorities to be considered for future renewable energy projects.

The research team gathered data and information through an examination of literature and interviews with subject matter experts familiar with coastal facilities and with experts in the renewable energy sector. The team conducted two case studies of US Coast Guard Station Monterey (CA) and Naval Air Station Corpus Christi (TX) to provide additional context for the adoption of sustainable renewable energy at coastal facilities. Additionally, research was conducted on mechanisms for microgrid financing to demonstrate how a facility may finance microgrid installation and further adoption of renewable energy and microgrids.

Researchers found that there are some common core challenges for installing and using microgrids. These challenges include zoning issues, environmental considerations, infrastructure barriers, financing issues, conflicting safety standards, technical obstacles, and administrative hurdles. Researchers found that some challenges can be lessened, avoided, or accounted for with advance preparation and awareness ahead of time.

Further analysis of region-specific challenges would provide more context for consideration of sustainable energy and implementation of microgrids. Further study is also required to understand the details of an
appropriate financial acquisition agreement with a quantification of the benefits and costs of microgrids over time. Finally, the processes for contracting out microgrid design and construction and identifying suitable contractors is recommended.

**Keywords**: energy, renewable, sustainment, solar, wind, battery, microgrid, storage, infrastructure, resilience, adoption, photovoltaic, PV, business model, technology, land use, zoning, permitting, regulation, regulatory, law, legal, policy, interconnection, utility, power, power purchase agreement, PPA, financing, funding, institutional, administrative, barriers, challenges, procedure, environmental, coastal, navy, coast guard, EUL, enhanced use lease

**Background**
Recent extreme climate events and adversary actions have highlighted the importance of resilient energy supplies. While energy costs are expected to continue to rise, Department of Defense (DOD) facilities' reliance on the fragile civilian electrical grid creates vulnerability towards outages.

Renewable onsite generation is an excellent candidate for improving energy security and can help meet new DOD climate goals. Although renewable energy is now cost-competitive with traditional energy sources, there are challenges to implementing new technologies at installations. According to DOD renewable energy users, renewable generation assets by themselves have merely served to help lower energy costs and potentially free up funding for other efforts. In order to improve resilience, renewable generation must be paired with grid-forming energy storage or microgrids that are able to continue operating and supplying power to facilities even if the primary energy source (i.e., the power grid) is unavailable.

Energy is generally highly regulated, and changes to energy infrastructure on installations are covered by a variety of laws and policies. With the rapid changes in energy technology, microgrids may be subject to policies and laws that were not drafted for this type of technology or the emerging energy systems. While renewable energy assets and microgrids have been in use for many years, they are often seen as emerging technology. Thus, implementing renewables effectively requires overcoming a number of technical, financial, legal, and policy challenges. Awareness of these barriers to implementation and maintenance ahead of time enables facilities to address common hurdles early in the process rather than as they arise or after commitment to a microgrid is made. This preparation means facilities can be in a better position to meet resiliency goals and manage adverse energy conditions.

The research team initially consulted with Naval Facilities Expeditionary Warfare Command and other facilities that were interested in acquiring renewable or microgrid technologies. Inquiries revealed that many facilities have difficulty maintaining existing renewable systems. Researchers originally planned to create a Do-It-Yourself guide to implementing small scale renewables and microgrids, but based on these consultations, the research team explored alternative means of microgrid acquisition and ownership. This process included law and policy analysis to understand challenges involved in the process of design and implementation.

The team examined a financing model where energy generation and storage assets on bases would be owned and operated by one or more contractors and financed through purchasing the power generated at a premium. With this approach, the federal government can better examine the various paths to
implementing and sustaining renewable energy generation and have examples of an acquisition method whereby a contractor will maintain the assets without large upfront acquisition costs.

Data was collected through study of academic literature, industry reports, and government publications, as well as interviews with subject matter experts representing coastal facilities and the renewable energy sector. Additionally, the research team consulted with installation staff at U.S. Coast Guard Station Monterey (California) and Naval Air Station Corpus Christi (Texas).

Findings and Conclusions
The research team found that some renewable energy generation assets that exist on naval facilities are inoperable due to the lack of personnel qualified to service them. Some simply serve to lower energy costs as opposed to increasing resilience and decreasing their carbon footprint to meet state and federal emissions targets. Compounding this problem, many of these systems are custom-built for the facility in which they operate, so the knowledge of these systems’ inner workings is concentrated in just a few individuals. Challenges also exist in the implementation of new projects due to legal, regulatory, and implementation hurdles that affect the time for a project to be implemented. Financing barriers exist in funding renewable energy and energy storage projects because of the large upfront cost, slow payback for renewable generation, and lack of means to adequately quantify the resilience benefits of energy storage when conducting return on investment analyses.

Results demonstrated that in order to promote the successful adoption of renewable energy assets, facilities should understand restrictions with land use boards and pursue zoning exceptions in the face of potential antiquated zoning laws. Environmental and safety considerations should be incorporated early, as well as the training of personnel prepared to support maintenance of the assets. Facilities need to address their relationship with the utility provider in order to incorporate a microgrid into existing energy infrastructure, identifying interconnection issues early on, and factoring time for collaboration with local, state and federal partners to implement new technology. Site-specific institutional and administrative barriers resulting in slow and/or complicated implementation may also need to be addressed. Additionally, adopting a paradigm of contractor-owned and operated microgrids on facilities, financed through a power purchase agreement, enhanced use lease, or similar mechanism is recommended.

Recommendations for Further Research
Sustainable energy at Department of Defense (DOD) installations is subject to a dynamic context: increased demand for resilient energy supplies, lower costs of renewable energy, increased availability and use, government incentives, and reduced emission targets are transforming some energy systems. This transition likely will include decentralized energy generation and storage systems, new technology, and new financial and contractual mechanisms to account for energy users also being energy producers. Researchers’ findings and this reality sets the tone for future research.

Further analysis of region-specific challenges would provide more context for consideration of sustainable energy and implementation of microgrids, including legal and policy issues and climate-specific design factors.

In addition, further research is needed to determine the most viable contractual means to secure acquisition of contractor-owned and operated renewable and microgrid systems. Researchers concluded
that the most viable path forward would be similar in nature to a power purchase agreement, where the DOD buys energy generated from the renewable and microgrid system at a premium, but it is unclear if a specific contractual vehicle will allow the DOD to do this in a way with a higher-than-market-rate energy cost.

Further research is also recommended to quantify the benefits of microgrids and energy storage over time so that the DOD can properly assess the value of their resilience benefits and assign an appropriate price tag.

NPS-21-N030-A: A Cost Benefit Analysis of Transitioning the USN to a Single Fuel Type

Researchers: Dr. Ryan Sullivan, Dr. Susan Aros, and Dr. Simon Véronneau
Student Participation: LCDR Andrew Camarata USN, LT Cody Kinser USN, LT Crystal Kube USN, Ms. Minkyung Julia Stevens CIV, and Mr. Noe Valenzuela CIV

Project Summary
Fuel distribution and its availability is key to maintain force posture during all phases of a conflict. Given the great power competition (GPC) increasing between the U.S., China, and Russia, and a shift to distributed maritime operations, it is important to assess the cost benefit of changing the fuel distribution to a single fuel type. The Naval Postgraduate School (NPS) proposes to conduct a cost benefit analysis (CBA) of switching entirely or partially to JP-5 fuel as opposed to the current multiple fuel types used on ships, aircrafts, and vehicles. Specifically, this research addresses these main questions: If the Navy adopted a policy allowing a 50% JP-5 and 50% F-76 mixture to be issued to surface vessels in lieu of F-76, what would be the cost benefit? Would this policy improve historical turnover rates of the Department of Defense's JP-5 inventory? What infrastructure investments are necessary to adopt a single-type Naval fuel?

We use past list purchase cost and standard sales prices for JP-5 and F-76 as our primary data sources to calculate potential savings from shifting to the SFC. Regression analysis is used to calculate the estimated purchase costs and sales costs for fuel under the current two-fuel concept. The predicted consumption figures for a single fuel concept (SFC) were used to predict the total fuel cost of JP-5 for future years as a single fuel in the fleet. We find significant cost savings by switching to a single fuel concept instead of a fuel policy mixture of using 50% JP-5 and 50% F-76. If the purchase and sales prices of JP-5 remain the same upon implementation of the SFC, there is potential for substantial savings for the government.

Keywords: naval fuel, supply chain, cost benefit analysis, CBA, JP-5, F-76

Background
Fuel distribution and its availability is key to maintain force posture during all phases of a conflict. Given the GPC increasing between the U.S., China, and Russia, and a shift to distributed maritime operations, it is important to assess the cost benefit of changing the fuel distribution to a single fuel type—more specifically, looking at the benefit of pooling inventory and simplifying distribution to a unique JP-5. NPS
proposes to conduct a CBA of switching entirely or partially to JP-5 fuel as opposed to the current multiple fuel types used on ships, aircrafts, and vehicles. Fuel distribution and its availability is key to maintain force posture during all phases of a conflict.

We use past list purchase cost and standard sales prices for JP-5 and F-76 as our primary data sources to calculate potential savings from shifting to the SFC. Regression analysis is used as our prediction model to calculate the estimated purchase costs and sales costs for fuel under the current two-fuel concept. Then, the predicted consumption figures for an SFC were used to predict the total fuel cost of JP-5 for future years as a single fuel in the fleet.

**Findings and Conclusions**

This report analyzes the feasibility of switching entirely or partially to JP-5 fuel as opposed to the current multiple fuel types used on ships, aircrafts, and vehicles. A CBA is provided which recommends immediate implementation of the single fuel concept in a phased rollout to cut costs, simplify the supply chain, and provide a long-term solution to a growing logistics problem.

First, we find significant cost savings by switching over to a single fuel concept instead of a fuel policy mixture of using 50% JP-5 and 50% F-76. If the purchase and sales prices of JP-5 remain the same upon implementation of the SFC, there is potential for substantial savings for the government. The cost savings for each scenario we provide (low end vs. high end of 30-year shipbuilding plan) show significant savings possible in future years by switching to an SFC. Based on our calculations, the Defense Logistics Agency can procure JP-5 as a single fuel for $227M to $262M less over the next decade. Additionally, the United States Navy would subsequently save between $86M and $99M over the next decade by switching to JP-5 as a single fuel.

Second, a policy of switching over to an SFC would dramatically impact turnover rates of the Department of Defense’s JP-5 inventory. Notably, the increase would take place since much of the Navy would be operating with only one fuel type (i.e., JP-5) if implemented in full. Based on the significant increase in the amount of JP-5 that would be necessary to implement the SFC, we recommend a phased rollout. This will allow time for adjustments to the supply system as well as allow time to assess unforeseen effects of an SFC on ships. The rollout plan consists of three phases held over the course of the next several years to conduct analysis, allow government-used refineries time to shift production to JP-5, and mitigate risks associated with unforeseen damages possible to ships after the switch to JP-5. Distillate fuels similar to F-76 are readily available across the world and are used by other militaries as well as merchant ships. The U.S. could use these other replacement fuels as an emergency source of fuel if JP-5 as a single fuel is disrupted in the future. However, the most important fuel to protect for future operations is JP-5 given that it is the sole fuel used in our maritime aircraft.

Lastly, the 30-year shipbuilding plan lays out the current force structure and predicted future force structure. The current number of naval vessels is 296 with the goal of 321 to 372 manned vessels and 143 to 242 unmanned vessels. By increasing the number of vessels, it could cause a heavy strain on the current underway replenishments, especially considering the requirement to carry both JP-5 and F-76.
**Recommendations for Further Research**

We recommend conducting research into the need to increase the size of the U.S. Navy’s refueling fleet to support the increase in size of the fleet. The 30-year shipbuilding plan lists a small increase in fleet logistics ships, but it might not be enough to support the increased fleet size in a contested environment. Additionally, we recommend adjusting the analysis to demonstrate the improved efficiency that is possible by utilizing the single fuel concept (SFC) on tankers.

To fully implement the SFC, the costs associated with the transition to SFC should be examined. These costs include things such as tank cleanouts onboard ships, reconfiguration of piping systems and storage tanks, changes to distribution of fuel onboard Military Sealift Command ships, and aspects of the transition that cannot be easily monetized such as unforeseen maintenance from long-term use of JP-5 on equipment previously run on F-76.

Fuel blending is an area of research that might help increase availability of JP-5 without completely ceasing F-76 production. Research should be conducted on both the feasibility and cost impacts of doing some ratio of a fuel blend. This would provide the Navy with an alternate to the current fuel set up or the SFC.

Refineries will have to significantly increase JP-5 production to keep up with the demand from implementing an SFC. Therefore, research should be conducted into the feasibility, timeline, and costs associated with commercial refineries making the switch from diesel fuel to JP-5, as well as how these factors would affect the timeline for implementing an SFC. Additionally, any risks involved in this change to the supply chain should be examined.

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**NPS-21-N057-A: Deep Analytics for Readiness Impacts of Underfunding Spares Backlogs**

**Researcher:** Dr. Ying Zhao  
**Student Participation:** No students participated in this research project.

**Project Summary**

It is important to research and adopt advanced and deep business intelligence (BI) analytics to understand the entire spectrum of the Navy logistics enterprise. The ultimate goal is to enhance total force readiness and project combat power across the whole range of military operations and spectrum of conflict at any time.

In this study, we consider the use case that Navy Ships’ aviation and maritime units order spares from their general funds to fill modeled allowances. The objective is to apply advanced business intelligence methodologies and tools to conduct comprehensive statistical and deep analyses of the readiness impacts resulting from not funding spare part requirements.
The research needs to 1) compare fleet demands against requirements in a financially restricted work queue (FRWQ), where, when not funded, spare requirements accumulate awaiting resourcing, 2) assess items in an FRWQ against high priority demands such as in a casualty report (CASREP) and an aviation unit’s casualty report (i.e., non-mission capable supply [NMCS]), and 3) design a tool that periodically scores and prioritizes the items in an FRWQ.

We examined two BI methods: baseline method fused from the Department of Defense (DOD) logistics and supply guidelines and a deep unsupervised machine learning (ML) method named lexical link analysis (LLA) for two data sets to address the needs.

We demonstrated the LLA methodology is able to discover association patterns. We also compared the items prioritized by the LLA method with ones by the baseline methodology from the DOD logistics and supply guidelines. The resulted research has the potential to deliver the design and implementation to periodically score and prioritize FRWQ items and inform the most efficient and effective method of stocking, forward staging, or contracting for the materials that have the highest likelihood of demand.

**Keywords:** financially restricted work queue, FRWQ, business intelligence, machine learning, artificial intelligence, non-mission capable supply, NMCS, casualty report, item mission essentiality code, intermittency, coefficient of variance, causal learning

**Background**

Navy ships’ aviation and maritime units may not have enough funding to buy spare parts. The requirements accumulate in an FRWQ awaiting resourcing. In the meantime, the systems with these parts support are still fielded, and the fleet still generates requirements to replace these parts. The goal of the study is to conduct a comparison of fleet demands against requirements in an FRWQ and assess these requirements with high priority demands linked to maritime units’ CASREPs and aviation units’ NMCSs.

Two methodologies are considered.

#1 - Baseline methodology: we first studied the guidelines and methodologies of scoring and prioritizing items based on the DOD Manual 4140.01-V2 (DOD, 2018). With respect to their impact to the weapon system and aviation readiness data from CASREPs and NMCSs, the DOD Manual 4140.01-V2 describes that two categories of measurements (i.e., the weapons system criticality and fleet demand) are needed to prioritize items. The weapons system criticality is measured by the Item Mission Essentiality Code (IMEC, DeHart, 1986) or Weapon System Group (WSG) code. CASREPs are linked to IMEC or WSG codes. CASREPs are linked to IMEC or WSG codes.

The fleet demand is based on the following points for scoring and prioritizing items:

- **Coefficient of variance points:** Calculated as the ratio of the standard deviation of the demand to the average demand.
- **Intermittency points:** Calculated as the percentage of total historical demand periods (e.g., months in a year) that have non-zero demand.
- **Platform/type points:** The overarching idea is that afloat units are given higher priority than shore units. Units that are deploying soon are highest priority versus low priority units, such as those in extended shipyard availabilities. Even the lowest priority afloat unit would still receive slightly higher points than a shore unit.
#2 - LLA methodology: the unsupervised ML LLA can be used to improve prediction (Zhao & Mata, 2020), detect anomalies (Zhao, 2020), and sort/rank important information (Stevens & Zhao, 2020). LLA describes the characteristics of a complex system using a list of word features. LLA automatically discovers word feature pairs and displays them as word feature networks.

The rationale of using LLA is that it can be used as a “market basket analysis,” where items that appear in the same context are considered associated or linked. Two items are linked if one item is demanded, and the other item also is demanded. LLA applies causal learning (Pearl & Mackenzie, 2018) and computes counterfactual proportion difference as the strength of item associations. We hypothesized that 1) items that appear together in the same baskets are associated with the same cause, so they could be demanded together; 2) centrality measures from the LLA word feature network provide mechanisms to score and prioritize items in an FRWQ, similar to other network analysis applications, for example, ranking people in a social network (Center for Computational Analysis of Social and Organizational Systems [CASOS], 2009), a gene in a biological network (Girvan & Newman, 2002), or a page of high importance on the internet (Brin & Page, 1998).

**Findings and Conclusions**

The historical raw demand data sets were used to compute priority scores of items based on the baseline method and LLA method. The FRWQ data sets are usually published periodically to the supply officers’ community. There are two data sets used in the use case:

- **Raw Demand Data Set 1 (Aviation):** Historical raw demand for items related to aviation readiness and NMCS
- **Raw Demand Data Set 2 (Maritime):** Historical raw demand for items related to maritime parts and CASREPs

LLA was applied to both data sets, yet its application to the Maritime data set was more meaningful since it contains a data attribute Job Control Number (JCN) that is used to group the items into a same requisition time or “basket.” Each basket identifies all National Item Identification Numbers (NIIN) and ship type (hull type) as unique items that are ordered in the same context as identified using the attribute “JCN.” JCN is a group number indicating when and where an item is ordered. There are 611,335 unique baskets (i.e., JCNs) and 280,762 unique items in this data set. We found 2,093,633 statistically significant associations that were used in the LLA analysis to determine the priority of an NIIN.

FRWQ items have been prioritized and ranked meaningfully and reasonably from the baseline methodology and have been validated by subject matter experts (SMEs). We found that association patterns discovered by LLA are meaningful based on the SMEs’ evaluation (SME, Hypothesis 1). However, the association patterns in this use case do not conclude better and more meaningful rankings of the items than the baseline method based the SMEs’ evaluation (Hypothesis 2). From the correlations of LLA scores and baseline points, LLA suggests using the “degree out weight” scores as the total estimated impact to other items’ probability of demand (POD), which has a correlation 0.34 with the baseline total points. This indicates LLA’s centrality measure “degree out weight” does not use demand as signals for deciding the importance of an item. This may also indicate the hypothesis of causality learning that one item’s demand might cause another item’s demand may not fit this problem.
The low-demand and high-impact items may not exist in an FRWQ data set. For example, the IMEC code defines the items that are highly important so that they usually fail less; thus, they are generally in less demand. However, should these items fail such as CASREPs, their impact to other associated items’ POD are not as obvious as in predicting the probability of failure in different LLA applications (Zhao et al., 2021).

Based on the results, a recommendation is to use the baseline methodology as the foundation for the design of an application to score and prioritize the items in an FRWQ periodically. The tool should take an input of FRWQ and match/score it against raw demand data from the ship and the IMEC code and platform/hull priority from the corresponding databases, and it should output a priority list of items.

**Recommendations for Further Research**

The resulted research helps improve and determine the most efficient and effective method of stocking, forward staging, or contracting for the materials that have the highest likelihood of demand, balanced with the potential impact of failure, spare, and the improvements of total readiness. The results also call for further research of deep analytics including lexical link analysis, machine learning (ML)/artificial intelligence and other supervised ML methods.

1. One future research recommendation is to derive item priorities and financially restricted work queue decisions using one set of historical data and test on another to see if the prioritizing methods would reduce casualty reports and non-mission capable supply.
2. Navy ships may also need to adopt more deep business intelligence (BI) analytics for a wider spectrum or end-to-end logistic planning. Future work also includes a review of business processes at a holistic level to plan for a whole class of ships or a whole fleet for a period (e.g., the CVN-74, USS John C. Stennis group for last a few years).
3. For the long-term, to perform more feasible deep analytics and other BI methods, more and accurate data are needed. For example, a study could collect consequences, feedback, penalty, or reward data on item prioritizing and resource allocation decisions, which might actually impact future readiness.

**References**


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NPS-21-N104-A: Warfare Analysis of Contested Logistics Agility

**Researchers:** Dr. Jeffrey Appleget COL USA Ret., CAPT Jeffrey Kline USN Ret., Dr. Robert Burks COL USA Ret., and Ms. Jane Barreto

**Student Participation:** Approximately 150 students from the Wargaming Applications and Joint Campaign Analysis Courses.

**Project Summary**

The research spanned four distinct lines of effort:

The first research was the fall wargame conducted in the South China Sea in a Denied, Disrupted, Intermittent, and Limited (DDIL) bandwidth environment. The research task was to examine an effective logistics task force command and control (C2) structure that enables fuel and ammunition delivery to a USN/USMC task force. Delays in resupply were driven by two key factors: poor planning and coordination and minimal communication.

The second research line of effort was a winter JCA mini study. This study compared a hub and spoke “push” logistic system to today’s centralized supply response system to support and sustain Western Pacific operations in contested environments. The hub and spoke system was more resilient by being less dependent on centralized C2 and having closer supply sources to forward bases.

The third research was the spring wargame that assessed how the integration of unmanned logistics forces affects the ability to sustain combatants during conflict. Unmanned assets were most effective for the delivery of smaller loads. The unmanned surface vessel (USV) did provide a significant contribution to Naval force sustainment.

The fourth research line of effort was a summer JCA mini study. This effort shifted from supply of forward bases to the question of medical evacuation from distributed land and sea forces in the Western Pacific. To meet “golden hour” medical response and longer-term care, it was found that damage control
surgical (DCS) units are required to be established within one hour transit time from an expeditionary base, and a Level III/IV hospital capability should be established in Darwin. The physical distance of the DCS from the bases depends on lift and field availability.

**Keywords:** logistics; unmanned; command and control; C2; denied, disrupted, intermittent, and limited; DDIL; unmanned surface vessel; USV

**Background**
The purpose of this study is to inform OPNAV N4 on concepts and technologies that will enable a more agile logistics force in a contested environment. New knowledge developed will include the effectiveness of unmanned systems as logistics platforms and the C2 requirements that will enable such a force.

**Research Methodology:**
1. Design, conduct, and analyze a logistics C2 wargame.
2. Winter 2021: Integrating fall wargaming results; conduct a follow-on contested logistics agility study.
3. Spring 2021: Incorporating results from the Fall wargame and the Winter Joint Campaign Analysis (JCA) course; conduct a study of the integration of unmanned assets into the logistics force.
4. Summer 2021: Using results from previous wargaming and JCA studies; additional Joint Campaign Analysis initial technology injects based on feedback from phases 2 and 3 and additional OPNAV N4 sponsor.
5. Prepare and deliver briefings and written reports of the results.

Wargaming data collection methodology is described in detail in *The Craft of Wargaming* (Appleget et al., 2020).

**Findings and Conclusions**
Logistics C2 wargame findings: Delays in resupply and lack of maintenance of an updated common operating picture of the battlefield resulted in the need of the logistics task force to adapt to changes in supply, in some cases doubling resupply throughput. These delays were driven primarily by two factors: planning and communication.

De-centralized Logistics C2 mini-study findings: To lessen the vulnerability of a logistics C2 system, a hub and spoke logistic system where forward supply depots provide supplies to forward Expeditionary Advance Bases is found to be the most advantageous method for delivery of supplies to first island chain bases in a contested South China Sea environment. Compared to the current demand-based centrally controlled logistics system, a decentralized Command and Control logistic concept where each base is logistically supported by a pre-staged supply depot featuring logistics craft located no more than 1000 nm away proved to be more resilient in a contested environment. Specifically, the forward supply depots are resupplied every four weeks from a major port of debarkation without demand signal, whereas the Expeditionary Advanced Bases on the first island chain are resupplied by the forward supply depots as needed via demand signal. An unmanned logistics sea plane concept proved to have a quantitatively positive effect in this decentralized system.

Integration of unmanned logistics forces affects the ability to sustain combatants during conflict.
Unmanned assets wargame findings: Unmanned assets were most useful for the delivery of smaller loads. The Expeditionary Advanced Base was sustained in a combat scenario using only unmanned forces launched from the offshore MSC ship. The relatively low capacity of the unmanned assets was offset by their increased numbers. Only the USV, with its significantly larger capacity, was able to supply a meaningful amount of assets to the surface Naval forces.

De-centralized medical evacuation mini-study findings: To meet “golden hour” medical response and longer-term care, it was found that damage control surgical (DCS) units are required to be established within one hour transit time from an expeditionary base, and a Level III/IV hospital capability should be established in Darwin. The physical distance of the DCS from the bases depends on lift and field availability. A notional system of forward expeditionary bases and ships operating in distributed operations across the Western Pacific was created in a SIMIO simulation package to analyze the requirements for various levels of medical evacuation. The need for EABs to be dispersed throughout the first island chain and distances between them drove a requirement for a dedicated DCS to be co-located within a one-hour lift from the EAB. The Army’s use of H-60s for medivac proved to be insufficient at higher levels of demand, whereas the Marines’ MV-22 provided coverage at higher demand periods. The Sea Wing in Ground (SWIG) capability was found useful for ship to shore transfer, particularly in distributed operations when an afloat surgical capability is not available.

**Recommendations for Further Research**
Clearly, the logistics command and control (C2) structure will require further examination as new assets, both manned and unmanned, are integrated into the logistics force. Additionally, optionally manned platforms may need to be examined for their utility as a logistics force asset. Vulnerabilities of the C2 network and the logistics force itself need to be continually assessed as potential adversaries will be developing new and more effective interdiction techniques.

**References**

**NPS-21-N104-B: Naval Logistic Network for The Great Power Competition and Operation in Contested Environment**

**Researchers:** Dr. Geraldo Ferrer and Dr. Margaret Hauser

**Student Participation:** No students participated in this research project.

**Project Summary**
Logistical support for U.S. naval forces has not met the test of a contested, degraded, or denied environment against a capable enemy since World War II. Recent conflicts were held against enemies with limited ability to disrupt the U.S. Navy’s supply chain. However, it is possible that in future scenarios the supply chain supporting U.S. forces would be targeted and under serious threat. The nations of concern to our national security, such as China, Russia, and to some degree North Korea, have abilities to deny free movement in some environments and target key supply chain enablers. This research evaluates
different methods of distribution logistics and different logistic vessels in a contested environment in the Indo-Pacific Command (INDOPACOM) area of responsibility (AOR). We enumerated multiple routes connecting potential sources of supplies to potential destinations in the South China Sea. We developed these routes using a cost and risk assessment. We selected the route, vessel, and timing of supply trips using a mixed integer linear program (MILP) to identify the lowest expected delivery cost. The objective value takes into consideration the distance traveled and the risk due to the proximity to the contested environment. The model provides useful motivation for the development of alternative logistics vessels and insights into the characteristics of those vessels such as speed, cargo capacity, range, and cost.

**Keywords:** contested environment, risk-based routing, risk-based logistics optimization, resupply scheduling, multi-stop supply route

**Background**

Combat logistics force (CLF) ships currently provide underway replenishments, but these vessels are not designed to operate in a contested environment. The loss of a handful of these vessels would have major implications for U.S. Navy surface operations (Krenz, 2018).

This study builds on previous and current research on Navy supply chains in contested and denied environments at the Naval Postgraduate School; the main studies are highlighted below.

- Colburn (2015) designed a MILP that optimizes the ability of “mini-CLF” vessels to deliver fuel to surface action groups (SAGs) and forward deployed units at sea including anti-ship ballistic missile (ASBM) threats (Colburn 2015). The proposed “mini-CLF” vessel is either a reconfigured Littoral Combat Ship/Joint High-Speed Vessel (JHSV) or a new class of logistical support ships.
- Krenz (2018) extended the “mini-CLF” model under ASBM threats to include the supply of fuel, stores, and ammunition to SAGs and forward deployed units at sea (Krenz, 2018). An interesting result of this study was the importance of a rolling time horizon: “a planning horizon that is too short can result in highly suboptimal solutions” (Krenz, 2018).
- Sorenson (2020) proposed a MILP for maximum network flow, which provides vessel configurations and routing assignments to maximize demand satisfied (Sorenson, 2020). The study recommended conventional CLF assets to be routed through low-risk nodes while defended or inexpensive vessels could be routed to higher risk destinations.
- Dougherty et al. (2019) analyzed the suitability of various vessels to provide logistics support to forward deployed littoral units (Dougherty et al., 2020).

We analyzed different methods of distribution logistics and different logistic vessels in a contested environment in the INDOPACOM AOR. The results of this analysis support “what-if” scenarios and force planning for a possible contested environment situation in the future.

Our study uses a MILP to include risk analysis in the distribution of critical supplies in a nominal unclassified concept of operation in South China Sea. Our model first develops a risk-based routing system, and then uses a MILP to minimize the expected delivery cost given a logistics distribution method and set of vessels. The MILP identified the combination of lowest cost routes, vessels, and timing to deliver supplies to each destination.
To incorporate risk, we stipulated that the area to the east of the second island chain is the least risky, followed by the area between first and second island chain, and finally the highest risk being in the South China Sea, west of the first island chain. We assumed three kinds of supply (fuel, ordnance, and dry goods), delivered from three sources (Guam, Singapore, and Darwin) to five destinations (Brunei Bay, Subic Bay, Sasebo Bay, Yokosuka, and Okinawa). The routes connecting the three sources to the five destinations were finely segmented to avoid obstacles and non-navigable waters and to reflect the different risk levels in the three areas to the east, between and to the west of the island chains. The study considered both direct routes (from source to destination and back) and mixed routes (from source to multiple destinations and back).

**Findings and Conclusions**
The objective of this research is to evaluate the performance of different supply methodologies regarding ship types (making deliveries using CLF ships or smaller and more expendable assets) and routes (direct and riskier, or indirect and safer). A logistics network that incorporates risk is described and assessed using different ship classes.

Our method of analysis found optimal delivery schedules for 15- and 20-day time-horizons for both situations: using a limited number of CLF ships or using a larger number of faster and smaller ships (littoral combat ships, amphibious transport dock ships, dock landing ships, and joint high-speed vessels) retrofitted for the logistics mission.

The difference in time-horizons affected the results, indicating the need for a solution approach that could be usable in an unlimited or extended time-horizon to achieve true optimality. The MILP with an extended time horizon increases the computation time exponentially; this issue is a key factor for future research. A key feature of our model is that the model does not assume cyclical deliveries (i.e., deliveries at a predictable, repeated interval). Unpredictable timing and delivery methods (route and vessel) are more difficult for the enemy to attack. The model provides useful motivation for the development of alternative logistics vessels and insights into the useful characteristics of those vessels such as speed, cargo capacity, range, and cost.

**Recommendations for Further Research**
The objective of this research is to evaluate the performance of different supply methods regarding ship types (making deliveries using combat logistics forces [CLF] ships or smaller and more expendable assets) and routes (direct and riskier, or indirect and safer). A logistics network that incorporates risk is described and assessed using different ship classes.

Our solution exposed limitations in our approach to evaluate the supply methods in two ways:
1) Relying exclusively on CLFs is costly, so we tested solutions with alternative vessels. However, the alternative vessels have limited range and limited load capacity.
2) Short-time-horizons were necessary because the computation time required to solve the problem increases exponentially with the duration of the time-horizon.
To address these issues, we recommend a continuation of the analysis with the following modifications:

1) Modify the delivery approach to include drop points. Large CLFs would make the first part of the trip from the source to a safe place in the ocean closer to the destination, where it would deliver the cargo to smaller vessels. The smaller vessels would continue the delivery to the destination.

2) Develop a periodic review planning process as an extension of the 15- and 20-day time-horizons. For example, on the tenth day of each time-horizon, recalculate the delivery schedule using the current conditions as the new starting conditions of the next time-horizon. Carry the extension out for an extended period to identify convergence.

A classified version of this analysis would improve the insights gleaned from the model using more than notional data and a concept of operations.

References


NPS-21-N332-A: Blockchain and AI Technology in Support of Transparent Navy Logistics and Global Supply Chains (Continuation)

Researchers: Mr. Walter Kendall and Mr. Arijit Das
Student Participation: LT Carlos Correa FORNATL FAB, LT Philippe Tavares Alves de Siqueira BN FORNATL, Ms. Jane Yang CIV INT, Ms. Avantika Ghosh CIV INT, and Ms. Aroshi Ghosh CIV INT

Project Summary
Navy logistics supporting naval forces is a complex process involving the procurement and transportation of material and the data associated with maintenance. We build on our previous project, NPS-20-N362 investigating using blockchain for the provenance and authentication of food and parts (Kendall, 2019). For this research period, we focused on data/information as an asset to track, authenticate, and provide provenance for analytics and artificial intelligence (AI) models since blockchain provides a trusted distributed ledger that can record transactions through the life of the data. We also developed an open-source Hyperledger Fabric (HLF) network on a virtual server at the Naval Postgraduate School (NPS) to demonstrate serial number tracking of parts.
Our methodology involves two sets of use cases. The first example uses blockchain to ensure the integrity of datasets for analysis and AI development (Case 1). We provide the framework for implementing a support system for data scientists and analysts to assure the data used is reliable, tamper-proof, and documents provenance (Kendall et al., 2021). The second set deals with serial number tracking of parts and major sub-assemblies, such as aircraft maintenance, and is demonstrated through the Linux Foundation open-source version of HLF.

We provide the basic methodology for Case 1 on how blockchain can be implemented for managing datasets but did not create a Hyperledger Fabric network to demonstrate Case 1 (Kendall et al., 2021). However, for the second set of use cases, we provide a demonstration using the open-source HLF blockchain and show how blockchain could track serial numbers (including major subassemblies) to validate and provide provenance for aircraft maintenance, which could also be used for ground maintenance through the life cycle management process.

**Keywords:** blockchain, logistics, workflow, federated learning, machine learning, ML, artificial intelligence, AI

**Background**
The purpose of this research is to demonstrate how blockchain can be used to track logistics assets, such as parts and datasets. Blockchain is a tamper-resistant decentralized database/distributed ledger used in many security applications to provide proof of transaction where trust is implemented through distributed consensus and not centralized policy enforcement. This trusted ledger can record transactions, involving whatever asset is to be tracked. Smart contracts can embed legal knowledge, laws, and regulations, and enforce Navy logistics policy. Blockchain can also provide “provenance” of an item—such as food, part, or dataset—and trace back to the source of that item in case of contamination or counterfeit/defective parts.

We used a qualitative methodology that included two general logistic use cases: 1) Management of data for analysis and AI development and 2) serial number tracking. For Case 2, we created simple scenarios where aircraft items were tracked during various maintenance processes through a blockchain network and smart contracts would check for certain conditions that would simulate quality control and tracking. We demonstrated Case 2 on our open-source Hyperledger Fabric Network at NPS.

The purpose of our study is to further expand the possible uses of blockchain to include serial number tracking of parts used in maintenance and show how the blockchain tracks data assets in support of analytics and AI. The blockchain concept is represented by such technologies as Hyperledger, Everledger, and Ethereum. We use the open-source version of Hyperledger, specifically Hyperledger Fabric for the second year of the study, whereas we focused on the enterprise version of HLF as packaged by Oracle and IBM in the previous year of this two-year study.

We answered the specific questions from our research proposal below:
1. Have more granular and realistic use cases to apply solutions using an HLF-based blockchain.
   Using the use case approach and an actual demonstration of HLF, we show how the serial tracking use case, involving parts and major subassemblies assets that move from acquisition to squadrons, and maintenance depots are documented and curated throughout the blockchain network.
2. Understand how blockchain would interface with the last tactical mile and the extent the Navy can support the last mile.
   We showed how application programming interfaces (APIs) can be used to interface with existing and legacy systems.

3. How could blockchain provide data for analytics and machine learning and provide security?
   We showed through our architecture how blockchain, with its smart contracts embedding trust algorithms and immutability, could be used for federated learning, which would provide more trust from sensor data on the tactical edge all the way up to the strategic level to be used for strategic analytics and AI (Kendall et al., 2021).

Findings and Conclusions
Using the open-source version of HLF, we demonstrated that blockchain could be used for serial number tracking (Case 2). We showed how you could track major sub-components (such as a compressor on a jet engine). Although we did not demonstrate Case 1 on our network except conceptually, we believe that dataset errors can be reduced through smart contracts (Kendall et al., 2021). We also introduce the concept of “smart repositories” where data scientists/analysts could search for the trusted data, who has it, and get almost automated approval to access this data.

We found that using the “free” open-source HLF can be easily used to create a secure network of peer nodes that can generate a consensus for the legitimacy of both data assets and parts assets used during the maintenance process. A special concern with Navy logistics is the possibility of unreliable networks, especially from shore to ship. The blockchain protocol creates a multitude of copies of the blocks (the public ledger), and if connectivity is lost, the blocks will be updated once the network node communications are reestablished.

The major difference between the use of the open-source HLF and between IBM’s and Oracle’s implementation of HLF are the developer tools and application programming interfaces provided, and how the implementation would connect to the Navy’s legacy systems to reach the “last mile” such as on the ship. We found the open-source version of HLF easy to use, but the commercial systems provide real value-added capabilities since HLF alone cannot make an enterprise blockchain system that supports the existing logistics information system. However, this is not to discount the utility of using the free open-source version of HLF to demonstrate proof of concepts using HLF. We used an intern who was able to quickly learn the open-source version to implement a serial number tracking system using HLF. HLF generally uses existing technology familiar to most programmers but packages it into a network of public and private ledgers that keeps track of assets.

HLF provides a consensus/private network as contrasted by “proof of work” blockchain networks used in cyber currency, which are inefficient and not appropriate for a government entity. Are there alternatives to using blockchain? Yes, but blockchain promises a standard approach whereas alternatives do not have one unifying framework that could be easily adapted to existing systems.

Recommendations for Further Research
Our recommendation is to have the Navy set up its Hyperledger Fabric test network, which could be done on virtual servers and would require only one or two programmers as we demonstrated with having an intern set up our school network with relative ease. Project managers could then use these simple
demonstrations to then look at small pilot projects using permissioned enterprise blockchain to
demonstrate the usefulness of it to improve aspects of the surface Navy supply chain such as its use for the
tracking of parts and food including food safety. Another blockchain use is for maintenance log integrity.
Maintenance logs are generated through maintenance transactions, but often some data is wrong or not
updated, which can impact mission readiness or understanding of the true state of affairs. When that data
is extracted for analysis, there could be so many errors that impact statistical analysis, thus preventing an
understanding that would lead to better decision-making. We have encountered this problem many times
when using data for analytics and machine learning. Also, since blockchain is in essence a database, it
could be used as a source for almost real-time analytics and training sets for artificial intelligence since the
blockchain is never overwritten.

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NPS-21-N355-A: Evaluating Performance of Directional Sensors in Support of
Detecting and Tracking Targets of Interest in Real Ocean Environments

Researchers: Dr. Kevin Smith, Dr. Paul Leary, and Mr. John Joseph
Student Participation: LT Matthew Sheeler USN and LT Keegan McAllister USN

Project Summary
The goals of this project included the performance assessment of commercial off-the-shelf (COTS)
underwater acoustic vector sensors deployed on a variety of platforms in real ocean environments. To
achieve this, a significant field test was planned that involved several different sensors, platforms, and
acoustic targets. Using multiple, independent directional acoustic sensors, we were able to successfully
track targets of interest during the August 2021 field test. Using bearing estimates from multiple locations,
which did not need to be precisely synchronized, accurate target tracks were established. Limitations on
system effectiveness were primarily due to COTS sensor orientation data, sensor stability, and clock drift.
Bottom moored sensors provided the best performance since stability and dynamic orientation changes
were mitigated. Individual sensors performed well down to predicted signal-to-noise ratio limits and
provided bearing estimates within +/- 5 deg for detectable signals. Data analysis to date has focused on
multiplicate intensity-based processing while more advanced coherent-based methods have shown
promise for enhanced performance. Signals investigated included broadband, impulsive shots, broadband
ship noise, and narrowband tonals from expendable mobile anti-submarine-warfare training targets
(EMATTs). Analysis is continuing on a substantial data set collected during the August 2021 field test in
Monterey Bay.
The primary findings of this effort indicate that multiple, independent COTS directional acoustic sensors are quite capable of achieving accurate target tracking results but tend to be limited by built-in orientation sensors and internal clock drifts. In addition, bottom moored systems appear to provide the most stable and reliable results.

**Keywords:** acoustic vector sensors, target tracking, acoustic intensity processing

**Background**

The Environmental Division of N45 monitors environmental effects on naval system performance as well as marine mammal mitigation efforts during acoustic training events. The availability of simple to use systems for tracking various sources of sound during operational exercises would enhance their capabilities. Traditionally, when “multiple sensors” are discussed, this refers to coherent processing of sensor arrays, which is distinct from our approach here. The goals of this project included the performance assessment of COTS underwater acoustic vector sensors deployed on a variety of platforms in real ocean environments. To achieve this, a significant field test was planned that involved several different sensors, platforms, and acoustic targets. Due to COVID restrictions and delays in acquiring/integrating equipment, this field test did not take place until August 2021.

From August 2, 2021 through August 13, 2021, a field test was conducted in Monterey Bay that collected acoustic vector sensor data from multiple sensor types using different deployment strategies and in different locations. Multiple source types were also used to generate a variety of signals to analyze the performance of such sensors in operational environments. The systems used to collect data included the following:

- A Geospectrum Technologies, Inc 3D acoustic vector sensor (based on their M20 design) integrated onto the Monterey Bay Aquarium Research Institute’s cabled observatory, known as the Monterey Accelerated Research System (MARS). Data was collected from this sensor throughout the test.
- Two Geospectrum Technologies, Inc 3D acoustic vector sensor (based on their M20 design) stand-alone systems were placed along an approximate 80 m isobath, separated by about 10 km, just southwest of Santa Cruz. One system was able to successfully collect continuous data for nine days of the test. The other system was only able to collect data for three days of the test before a data storage issue occurred.
- Two Wilcoxon/Meggitt 3D acoustic vector sensors (based on their VS-301 design) were deployed as freely drifting tethers to a drifting buoy, which contained the batteries and data acquisition system. These sensors were able to collect approximately four hours of data.
- Multiple conductivity-temperature-depth (CTD) casts were made on various days of the testing, both on the Santa Cruz shelf as well as over the deeper MARS system. The deployment vessel, the National Oceanic and Atmospheric Administration (NOAA) R/V Fulmar, recorded its own navigational data for subsequent signal reconstruction.
- Continuous automatic identification system (AIS) ship data, including merchant vessel traffic off the coast of Monterey Bay, was collected throughout the test.
- Continuous meteorological environmental data was also collected by the NOAA weather buoy 46042.
The sources utilized to create varying signals of interest included the following:
- The broadband noise of the deployment vessel, R/V Fulmar.
- Two EMATT systems transmitting tones at 900, 910, 920 Hz and 1000, 1010, and 1020 Hz. Depths and headings changed based on pre-programmed tracks.
- Multiple lightbulb implosions at approximately 30 m depth.
- Distant merchant shipping noise.
- Local shipping noise.
- Marine mammal vocalizations.

Findings and Conclusions
The August 2021 test results are encouraging of the fundamental ability to track targets and provide reasonably accurate positional estimates from multiple sensors. Here, we highlight several limitations in the current sensors.

Orientation sensing
In all vector sensor systems that the authors have encountered thus far, the orientation sensors have been the most problematic aspect of analysis. Measurements of one yaw sensor repeatedly showed occasional rapid jumps in yaw by 180 degrees or more, which required manual correction. The data indicates that the sensor is twisting about its Z axis by as much as 6 degrees over the course of minutes. While some of this motion may be true, it does not seem believable that a weighted sensor deployed at 80m depth would exhibit this kind of motion. With the other problems observed with the orientation sensor, it can be difficult to trust if these smaller motions are true as well. Therefore, the processing done was completed with overwritten orientations, which is likely also not exactly correct. The results illustrate that in many situations, extremely small errors in bearing can have tremendous cumulative effects; thus, issues with yaw (which largely dictates the rotation of data from the sensor-frame into the earth-frame) can quickly limit the capability of these sensors for tracking at distance or in sensitive geometries. This issue could be resolved, though, with more dedicated effort.

Clock drift
While the stabilizing of clocks is a field unto itself, and not nearly as simple to address as the orientation problems above, drift in the clock driving the sampling of vector sensor systems is likely to contribute to the errors we observe. At some distances and geometries, two bearings, which are otherwise accurate but are incorrectly aligned in time, could also create substantial position error. The authors intend to continue with some verification in this area, but substantially more effort could be placed in stabilizing the clock sources for samplers in these systems. This is often highlighted in coherent processing applications, where processing between non-stabilized systems is effectively impossible. However, the results above show that even in non-coherent applications, this can contribute to potentially significant error. In non-coherent processing of sensors, it seems that some reasonable attention to clock stabilization, not near the level required for coherent systems, could make substantial improvement to the ability to track with vector sensors. Currently, drift appears to be on the order of seconds/day, which we believe can be improved considerably without resorting to impractically high-performing efforts.
Our approach successfully tracks targets using bearing estimates from multiple locations, which do not need to be precisely synchronized to calculate accurate tracks, especially for relatively slow-moving targets. Tighter synchronization is better, but the synchronization error tolerance in our approach is much higher than in coherent processing techniques. The advantage of this approach is its simplicity. Tracking targets with arrays of sensors requires significant logistical challenges as sensors require either synchronization signals (e.g., GPS synch pulses) or wired connections between sensors. In our approach, sensors may be simply battery powered and submerged.

**Recommendations for Further Research**

From our results, the limitations of our tracking process currently are due to non-acoustic aspects of our implementation, namely accurate orientation sensing, and possibly clock synchronization. We believe improvements could be made in both areas within reasonable efforts.

Further analysis should focus on the effects of time synchronization and error on the position estimates obtained. While these effects are difficult to verify, as there is no ground truth for timing available, some opportunities for experimentation do exist. For instance, receiver clock drift may be estimated by locating clean, short duration signals, which are clearly audible at each sensor and adjust the data’s timestamp to reflect the predicted travel time between locations. This is most easily done if the location of the source signal is precisely known. While it may not be possible to verify the true timing error exactly, it may be possible to clarify to what extent clock drift explains error in position estimates.

One important implementation which we hope to pursue in the near future is the similar tracking of signals from mobile towed vector sensors. Specifically, we plan to integrate a towed acoustic vector sensor on a Liquid Robotics Wave Glider unmanned surface vehicle for persistent mobile tracking and monitoring of the directional soundscape. This provides several advantages. The obvious advantage is that the mobile platform may be adaptively positioned to optimize the geometry of sensor locations to maximize the tolerance for small errors in bearing estimates in the final calculation of position. As we have shown here, large positional errors can result from small bearing errors when targets are in certain areas, such as very near the axis of sensors, or very far away. A network of mobile sensors could reposition over time, especially for slow moving targets, and drive this error towards zero, using consistency of position estimates as a proxy for error. Subtler advantages of this implementation include persistence as well as possible synchronization. We hope to continue these experiments during 2022, focusing on the combination of fixed and mobile vector sensors to track vessels, unmanned platforms, marine mammals, and other signals of interest.
**N7 - WARFIGHTING DEVELOPMENT**

**NPS-21-N105-C: Shoot, Move and Communicate – Increasing NSW Mission Effectiveness through AI/ML Augmented Unmanned Systems**

**Researchers:** Dr. Douglas Horner, Dr. Ruriko Yoshida, and Dr. Geoffrey Xie  
**Student Participation:** LT Bryan Lowry USN, LT Darren Kurt USN, and MAJ Larry Wigington USMC

**Project Summary**

Unmanned systems have significantly increased mission effectiveness over a wide range of military operations. By combining unmanned vehicles (UxV) through wireless networks into a single collaborative control structure, it further expands the possibilities. Multi-agent control is normally divided into either a centralized or distributed approach. Our prior research has developed a hybrid approach that combines them for a unique control solution. This project investigated limitations of an unmanned vehicle networked control system (UxV NCS) approach and found that ground operators required greater system flexibility to improve mission effectiveness. The main result of the study introduced a human on the loop (HOTL) component which permits human controllers to adjust the level of UxV NCS autonomy dependent on the mission scenario. Additionally, this work evaluates an opposing force’s ability to determine operational intent from the collective motion of the NCS. Called Red Cell analysis, the technique can be potentially used to improve operational deception through motion strategies of the unmanned systems.

**Keywords:** unmanned vehicles, UxV, UxV networked control system, UxV NCS, artificial intelligence, machine learning, unmanned systems control, wireless communications, networking, human on the loop control, Red Cell analysis

**Background**

Prior research developed by Naval Postgraduate School (NPS) faculty and students (Wachlin, 2019; Lowry, 2020; Kurt, 2020) developed a UxV NCS hierarchical artificial intelligence/machine learning (AI/ML) architecture that included three levels. At the lowest level is the control for the individual unmanned agent. This consists of the ability to set propulsion and actuators that permit the agents to fly an intended path or trajectory. The mid-layer provides optimal UxV position recommendations using an ML technique called Distributed Adaptive Submodularity. The top layer emphasizes more general Quality of Experience metrics like maximizing communications throughput.

Through initial discussions with NPS Defense Analysis students, Naval Special Warfare (NSW) personnel, and thesis students, the control architecture showed great promise, but a consistent criticism was the inability for ground operators to “more fully control” the UxV system. The approach provided a high level of autonomy and significantly reduced the necessary logistics support, but it would also need to:

1. Be more responsive to the immediate requirements of field operators.
2. Permit one or more UxVs to be controlled by field operators while the rest of the system adapted to this by moving the remaining unmanned systems into optimal positions.
3. Permit a full “continuum of control.” Field operators want the flexibility to have the system be fully autonomous with the option to have humans control all the unmanned systems individually.
4. Anticipate a future engagement where UxVs have weapons and full control would be required by humans.

To address these concerns, the architecture added a unique HOTL component in the top layer. The concept is, in part, a response to a more traditional human in the loop (HITL) control system. With HITL, humans are actively in the feedback decision loop. With HOTL, human oversight monitors the AI/ML system with the flexibility to make specific modifications where necessary. Through this addition, it permits both centralized and distributed control.

A second important study initiative was to determine whether the collective paths of the UxV NCS could be used to infer operational intent. In other words, could the UxV positions over time be used to infer the location of ground forces or could they be used to determine the mission goals? Just as we are starting to use AI/ML techniques for autonomous, networked control, it is likely that opposing forces will use some of these same techniques to determine our intent.

Using data collected from the 2017 Multi-Threaded Experimentation, two combined approaches were used to give predictive analysis to the ground movements of a SEAL element from the combined collection of UxV motion data. The first is called Auto-Regressive Integrated Moving Average (ARIMA). It was used to forecast the positions of the UxVs. A deep neural network (DNN) was used to infer the motion of the ground team based on the motion of the UxVs.

**Findings and Conclusions**

The Red Cell analysis showed that the ARIMA plus DNN showed promise for predictively estimating the position of a ground force based on the motion of a collaborative UxV NCS (Wigington, 2020). The research took realistic operational scenarios to validate the use of a UxV NCS to support NSW missions. Through discussions and analysis with subject matter experts, we were able to identify and address two areas of concern. The first was the ability to provide more flexibility in the UxV NCS control system by integrating an HOTL approach into the upper tier of the hierarchical structure for a “full continuum” of control that can be tailored to ground conditions. This control flexibility will be especially important in the future. It is based on the following assumptions.

1. The SEAL ground element should be able to control the system. This ensures that systems are positioned rapidly where they are needed and minimizes the logistic footprint associated with forward deployments.
2. A full continuum of control maximizes operational flexibility. At one end of the continuum, full autonomy is important when ground operators are busy. At the other end, full human control of all unmanned agents may speed the response and provide non-optimized communication and sensing based on specific scenarios.
3. Eventually, the UxV NCS may include weapons for force protection and projection. These will need to be controlled by human operators.
The second area of concern was whether the UxV NCS could be used to determine operational intent. A novel Red Cell analysis looked at the predictability of the UxV NCS for determining the operational intent of blue forces. Based on the analysis, it showed the technique could be used to determine operational intent.

**Recommendations for Further Research**
Future work will be required for integrating Red Cell analysis into the hierarchical control approach. This would consist of running the model on the recommend unmanned vehicles’ (UxV) motions to assess the predictability of the mission’s intent. When operational deception is deemed critical in mission performance, the system would generate a sequence of UxV positions that would make it more difficult to track the SEAL element and infer mission objectives.

**References**

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**NPS-21-N105-E: Bento Box—Modular/Recoverable Stratospheric Balloon Payload to Enable Artificial Intelligence for Small Unit Maneuver**

**Researcher:** Dr. Wenschel Lane

**Student Participation:** Maj Christopher Gallegos USAF and LT James Hansen USN

**Project Summary**
The research that was conducted on the use of a modular stratospheric balloon system to enable artificial intelligence for small unit maneuver (AISUM) combines the work of two master’s theses and a payload design effort conducted by Space Systems Engineering, Space Systems Operations, and Defense Analysis students and interns. By examining the barriers to operationalizing the stratosphere (Gallegos, 2021) and developing a high-altitude balloon (HAB) bus that can accommodate up to three payloads (Hansen, 2021), a suitable infrastructure that can potentially support AISUM concepts of operations (CONOPs) was identified. A software-defined radio (SDR) payload was configured to simulate a real-time video feed from multiple sources, including a remotely operated drone and ground forces, back to a joint operations center (JOC) location. This serves as one example of how a near-space platform can be used as a low-cost, disposable asset that supports AISUM and augments existing capabilities for operating in hostile, contested environments.

Additional feasibility testing was conducted to demonstrate the utility of such a system in the 3D battlespace as an independent operation with precision recovery capabilities. Building on previous work...
on autonomously steered parafoils deployed from a HAB bus, student interns researched parafoil deployment methods and used radio-controlled servos to characterize the flight dynamics of a CubeSat form factor carried by a parafoil. Flight times were limited due to the use of tethered balloons, but this testing demonstrated the feasibility for a parafoil to guide an asset to a targeted location.

The results of this effort indicate that a low-cost, simple solution like the Bento Box can support AISUM objectives. Commercial small satellite bus vendors have mechanical, electrical, and data interfaces similar to the Bento Box. The reliable and robust nature of these space-worthy systems with high technological readiness levels can be leveraged and adapted for successful use in the stratosphere.

**Keywords:** high-altitude balloons, HAB, over-the-horizon communications, unmanned systems, space systems, CubeSat, artificial intelligence, AI, small unit maneuver

**Background**

Operating in hostile, contested environments against technological peers is a growing concern across the Department of Defense, but the tactical advantages against future adversaries for Special Operations Forces (SOF) is especially important. The use of alternate means to maintain continuous airborne surveillance, uninterrupted communication, and accurate navigation inputs are critical for tactical maneuver elements to perform basic combat tasks and maintain situational awareness. The widespread use of unmanned, autonomous vehicles to offload dirty, dull, and dangerous tasks from manned systems speaks to the benefits of such systems; using HABs would provide this capability in the airspace between traditional air-breathing systems and space systems outside of the Earth’s atmosphere. As the SOF community looks to incorporate artificial intelligence (AI) and machine learning (ML), a potential low-cost system that increases force protection across domains could provide infrastructure to support Navy Special Warfare tactical maneuvers.

The CubeSat form factor, a small satellite based on a 10-cm cube (1U) weighing no more than 1.33 kg, has had a profound influence in low-Earth orbit for both commercial and government entities. Since its inception in 1999 for educational purposes, the CubeSat has matured as a global market within the satellite industry with a projected compound annual growth rate of 15.1% (Allied Market Research, 2021). However, obtaining and funding launch opportunities to space still presents a challenge to operational responsiveness. Despite efforts by the Operationally Responsive Space Office to pursue critical or enabling technology (Davis, 2015), satellites are not assets that are organic to, and deployable at, the squad level, which leaves SOF units competing for access to mission-support assets. The Space Systems Academic Group (SSAG) at the Naval Postgraduate School (NPS) has developed a HAB bus that conforms to the CubeSat form factor for educational and research purposes. By leveraging the CubeSat form factor, the HAB bus facilitates the adaptation of space technology that can be flown on small satellites to use in the stratosphere. Meanwhile, the mission life cycle can be reduced from the nominal two-year timeline for CubeSats (Lan, 2006) down to as short as three months. This HAB bus, which uses standard data communication protocols and power input levels for commercial-off-the-shelf (COTS) technology, has been used for student projects and theses to conduct near-space testing for spacecraft payload development (Correa de Souza, 2018) and perform CONOP feasibility testing for space-to-ground, beyond-line-of-sight (BLOS) voice communication relays in very-high frequency (VHF) with PRC-152 radios for a SOF use case (Swintek, 2018). Additional research was performed by Space Systems students in 2019 to investigate targeted recovery techniques, including an autonomously steered parafoil.
These previous research efforts served as building blocks for the Space Systems and Defense Analysis students who modified the existing HAB bus structure, named the Bento Box, to support multiple payloads and maintain flexibility for integration with marsupial vehicles with a “plug-and-play” mindset for mechanical, electrical, and software integration. Standard mission architecture and spacecraft design processes, along with agile principles, were used to develop the Bento Box, a payload, and a CONOP for this study.

Findings and Conclusions
The CONOP developed and tested for this study, which enables the exploitation of AI that can be used by SOF, consisted of a COTS software-defined radio (SDR) payload, which was used for a real-time, BLOS video relay. The Bento Box consisted of a payload mounting plate that facilitated mechanical assembly and integration, and the 2U CubeSat form factor from previous missions was maintained. Two balloon flights were conducted by the students using tethered weather balloons at an altitude of just under 500 ft to simulate the station-keeping capability of a large stratospheric balloon, like the Raven Aerostar, while complying with Federal Aviation Administration (FAA) regulations for systems weighing under four pounds. For both flights, there was no direct line-of-sight between a hexacopter drone and the user terminal; the ground distance separation between the ground station terminal and either the drone or user terminal was under 1 km. The ground station terminal served as the JOC, and the user terminal simulated ground partner forces (PF).

The first flight served as the initial field test for the SDR payload with a single video source from the hexacopter relayed to a user terminal. The maximum ground distance between the drone and the JOC was 853 m, and the ground PF terminal was 480 m from the JOC. This bent-pipe relay was successful, but adjustments in filters, amplifiers, and antenna components were made for the second flight, which incorporated three video sources; all video feeds operated on separate channels. In addition to the drone feed, ground PF were outfitted with a plate carrier camera, and both video feeds were relayed in real-time back to the JOC. A third camera was placed on the Bento Box itself, providing additional aerial coverage of the simulated PF patrol operation. The PF carried a receiver and six-inch display to receive target updates provided by the video feeds from both the drone and HAB (Hansen, 2021).

Targeted, autonomous recovery of low-cost, low-observable systems was also investigated by student interns as part of this study. As the autonomous steering had been previously tested, this part of the study focused on flight control and deployment testing of a parafoil with a Bento Box mass simulator, culminating in five deployments from a tethered balloon. Due to the small size of the parafoil and the low-release altitude (below 500 ft), the total flight time was approximately one minute. Although the lessons learned from these tests have not yet been integrated with the Bento Box, the results indicate that a larger parafoil and a separate, modular control system are likely needed to meet AISUM requirements.

These proof-of-concept tests showed that HAB assets can be a valuable addition in SOF operations (i.e., by enabling a remote advise/assist operation of a PF). The stratosphere has been identified as an underutilized regime that can augment existing operations, especially for SOF (Gallegos, 2021), but this system allows for rapid development of platforms that are AI-ready across multiple battlespace domains for operational use.
Recommendations for Further Research

The results of this effort indicate that while a low-cost, simple solution like the Bento Box is useful to study the feasibility of relevant concepts of operation (CONOPs), the current system has a low technology readiness level (TRL). By comparison, commercial small satellite buses are at TRL 9 and can be adapted for operational use in the stratosphere. Many have extensive space flight heritage, making these systems ideal candidates for use on near-space platforms. They also use commercial off-the-shelf technology, which drives the cost down and facilitates interoperability between subsystems and payloads. As onboard processing becomes an essential capability to utilize artificial intelligence (AI) and machine learning (ML) to affect the kill chain, systems and payloads that can accommodate and meet the necessary performance requirements become critical infrastructure as well.

A demonstration with a network of large balloons such as the Raven Aerostar, with adapted CubeSat buses implementing AI and ML algorithms on sensor data, could potentially provide meaningful results that would further inform the problem set for artificial intelligence for small unit maneuver. The inclusion of operational drones such as the Scan Eagle would be needed to validate the CONOP used for this study. Commercial products that are compatible with these types of drones already exist and could be integrated with a small satellite bus for such a test.

Future work on targeted autonomous recovery from a balloon system is needed to better understand the feasibility of possible solutions. Unmanned aerial recovery vehicles such as the Ronin and Night Fury developed by Sierra Nevada Company and the United States Air Force Academy, respectively, are included in the current trade space, but integration and testing with the Bento Box or similar system has yet been completed. Additional research into the use of an autonomously steered parafoil system as a possible solution includes investigating the use of larger parafoils, reliable deployment, and improving the flight algorithm to incorporate AI and ML.

References


NPS-21-N105-F: Predicting Effectiveness of Human-Machine Teaming

Researchers: Dr. Mollie McGuire, Mr. Aurelio Monarrez, and Mr. Tadashi Morishita
Student Participation: No students participated in this research project.

Project Summary
The current project investigated the ability of human operators to manage multiple ScanEagle unmanned aerial vehicles (UAVs). The future of unmanned vehicle (UxV) operations is transitioning to a one-to-many model where one operator will be expected to control multiple UxVs. To develop an efficient one-to-many model, it is first important to understand the limitations of the human operator. Operators were observed in four test scenarios where they managed up to four simulated ScanEagles. Performance assessments, operator feedback, and pupil dilation measures were analyzed to assess ability and cognitive load while managing multiple aircraft. The most common error when managing multiple ScanEagles was violation of airspace. All but one operator violated airspace at some point in time during testing. Neglect of aircraft in uncleared airspace as well as collision of two aircraft was observed in the management of multiple errors on multiple aircraft. Pupil dilation measures showed a significant increase from managing one UAV to managing two or more UAVs. This expected result indicates the additional cognitive load the operator experienced when managing more than one ScanEagle. This effort represents the first step in a continued effort to build an effective one-to-many UxV platform. Future research will examine the addition of autonomy to aid the human in UxV management and exception handling. This human-autonomy teaming dynamic needs to be researched in terms of appropriate roles for the human and autonomy to effectively manage multiple UxVs. Additionally, multi-domain UxV operations need to be considered, as the future of UxV operations will not be limited to a single domain.

Keywords: unmanned aerial vehicle, UAV, ScanEagle, human-machine teaming, operator performance

Background
The human-to-UAV ratio is decreasing as autonomy increases. Not only is a human capable of managing multiple UAVs, but in some circumstances, the human’s role is shifting away from controlling (i.e., performing tasks that are fundamental to flight) to more supervising (i.e., monitoring performance and handling exceptions if necessary). Under conditions of higher autonomy, a human is capable of controlling up to twelve UAVs (Cummings & Guerlain, 2007). However, when more human involvement is needed, the number goes down considerably. This is due to the cognitive resources needed to effectively control the UAV; the more the human is involved in the coordination and control of each UAV, the less cognitive resources are available to attend to other UAVs or to maintain situational awareness of the context and larger picture.

The present study observed various testing conditions with one operator managing multiple UAVs. Operators ranged in experience from beginner to advanced/expert to assess how operator experience.
impacts the dynamic. The UAV operators were flying ScanEagles and went through four testing sessions. In the first testing session, the operator performed systems checks and takeoffs for four simulated ScanEagle aircraft consecutively with emergencies occurring on each aircraft at separate times. In the second test, the operator managed four simulated ScanEagle aircraft with engine failures, forcing internal airspace deconfliction and prioritization of aircraft recovery. In the third test, the operator managed four simulated ScanEagle aircraft, 2x engine failures, and 2x uncontrolled climbs, forcing prioritization of emergency procedures and prioritization between airspace violation and emergency recovery. Finally, in the fourth test, the operator managed four simulated ScanEagle aircraft, each with a critical or catastrophic emergency, forcing prioritization of emergency procedures. The goal of the analysis was to assess where the breakdowns occurred when managing multiple ScanEagles with simultaneous errors. Additionally, the operators wore eye-tracking glasses to assess their attention and cognitive load throughout the tests.

Findings and Conclusions
There was a total of six operators that were observed that conducted four testing scenarios with multiple ScanEagles. They ranged in experience level from beginner to expert, with hours of ScanEagle flight time ranging from 5 hours to 715 hours.

Subjective performance assessments were made by a subject matter expert for each of the operators throughout each testing session. The performance assessment is broken down by test.

- In Test 1, all but one participant violated airspace. The exception was one of the most experienced operators, who pre-emptively killed the engine before hitting the maximum threshold. In addition to violating airspace, multitasking multiple ScanEagles resulted in leaving one UAV in uncleared airspace, two UAVs in the same airspace, and a mid-air collision with two UAVs during descent.
- In Test 2, two operators violated vertical airspace and three violated lateral airspace. In addition, one UAV dead engine went unnoticed until 400’ due to the operator handling two other UAV emergencies, and two UAVs were sent into co-altitude and co-airspace.
- In Test 3, three operators violated vertical airspace; however, there were not any lateral airspace violations. The majority of errors came in the way the UAVs were landed, with inappropriate approaches or landing short.
- In Test 4, two operators violated vertical airspace and one violated lateral airspace. In addition to airspace violations, a misdiagnosed error was observed, and a UAV descended below minimum altitude due to error.

Additionally, the operators reported on what they felt was challenging. Prioritizing the errors was reported as particularly difficult when there were multiple errors and they varied in type. Challenges with multitasking was a theme in the operator feedback, with one operator reporting that it was difficult to not get tunnel vision on a single error.

Pupil dilation measures were analyzed to see if they could provide insight on cognitive load of the operators. Pupil dilation when the operators were managing one UAV was taken as the baseline because this reflects normal operations. Before calculating the difference in pupil dilation from baseline, it was important to see if the other conditions showed increased pupil dilation due to task complexity. There was
a significant difference in pupil dilation between managing one UAV and all other scenarios except managing three UAVs. However, during the management of three UAVs, the operator was faced towards the sun, which causes the pupils to constrict, so the lack of a difference from baseline is most likely due to environmental conditions. The comparison in pupil size between the other conditions was taken as how much there was an increase over baseline for the rest of the comparisons. There was a significant increase in pupil size during Test 2. The other conditions were not significantly different. Overall, the pupil dilation measures suggest that multiple UAVs results in an increase in cognitive load, even by just adding one.

The performance evaluations, operator assessments, and cognitive load measures indicate that even the addition of one more UAV might be too much. This result is consistent with what was expected and serves to lay the foundation for future research testing human operators managing multiple UxVs with the addition of autonomy, making the management of multi-UxVs a human-autonomy teaming task.

**Recommendations for Further Research**

This study established the foundation in understanding unmanned vehicle (UxV) operators’ capacity in managing multiple unmanned aerial vehicles. When handling multiple exceptions, airspace violations were seen in all operators except one, and there were instances of unnoticed errors and an inability to take proper corrective action. With the direction of UxV operations going to one to many, it is important to understand the human capabilities and how the execution of one to many can be effectively executed.

The one-to-many model for UxV management needs to be developed in a human-autonomy teaming framework. Future research needs to examine what aspects of the task can be supported by autonomy, and what aspects should be supported by the human. Trust and reliance will be important to study in this framework as well. To what extent will the human trust the autonomy to carry out the tasks appropriately, and what would help alleviate human cognitive load in handling simultaneous errors? These are important to assess in future research.

Additionally, this study just assessed ScanEagle operators. It is important to also examine operators in a multi-domain UxV environment. The one-to-many dynamic will also extend to multi-domain control of UxVs. It is, therefore, important to understand the added complexity of diverse environments in the management of multiple UxVs. The challenges and errors that occurred in the present study were limited to one domain, with the same type of aircraft. What does exception handling look like when the errors are unique to the environment and differ among the various assets?

**References**


Researchers: Mr. Arkady Godin and CAPT Scot Miller USN Ret.
Student Participation: LCDR Christopher Jennings USN

Project Summary
The current geo-political situation requires Special Operations Forces to act at the speed of light. This requires all data to be digitized. Naval Special Warfare Command (NAVSPECWARCOM) puts a special emphasis on digitizing mission command to gain advantage over adversarial forces in speed and quality of planning and execution. NAVSPECWAR, due to its nature, conducts digital mission command tasks at the spear of the tactical edge.

Our primary research question is to apply understanding of the data maturation process to the innovation of the digital mission command. Our method is to identify where a significant return on a data value is hidden by using transformation from spatial-temporal representation to a temporal representation organized into temporal snapshots pointing to the spatial objects. This lets warfighters gain a speed advantage in a battlespace during the execution of the Orient phase in the Observe-Orient-Decide-Act loop. Understanding of a data value through the transformations provides our sponsors with informed appreciation on why operating with knowledge is a winning multiplier.

The result of the research proved that for contextually adaptive battlespace, it is paramount to have situational awareness. Analysis of data maturation informed that “projected” situational awareness is the most pertinent. It is obtainable only by accounting for continuing threats at the battlespace. This means that obtaining superior situational awareness is a continuous endeavor.

Our research concluded that it is imperative to integrate data with the meaning of the data as a first step in data enrichment to transform it to knowledge and beyond. We also concluded that adaptive situational awareness requires representing situations in event-driven graph data models. Finally, it is apparent that decision making requires aggregation over layers of summarized graph data models. We recommend using a multi-dimensional multi-hierarchical summarization engine that can imbed graph data models, non-graph data and models.

Keywords: OODA, Observe-Orient-Decide-Act, projected situational awareness, context, data maturation, Special Operations Forces, transformation, contextually adaptive battlespace, representing situations, event-driven graph data model, aggregation over layers of summarized graph data models, multi-dimensional multi-hierarchical summarization engine

Background
The focus of our study is to advance the topic sponsor’s command and operational requirements and capabilities requested by such requirements. The functional areas we have been asked to study support a modern definition of command and control named “digital mission control.” Our research study is synergistic with the sponsor’s requirements for innovation by pushing down the military logic from the application layer to the platform layer. This results in all shared reusable functions being organized in a platform layer. Our research team has concluded that modern operational requirements cannot be
fulfilled without reliance on a foundational data strategy acting as guidance for the system engineering platform and, on a software side, as a guidance to the reference architecture implementation. The results of our team’s research will aid “digital mission command” accomplishment because visionary data strategy will make it possible to have operational requirements that are not even imaginable with “as is” legacy data architecture.

Current knowledge of innovating “digital mission command” is highly dependent on the presence or lack of the foundation of a data strategy. If, in our case, “digital mission command” is driven by reference architecture implementation, which is supported by prototyping efforts, such investments are risky due to a likely lack of possible understanding of the future platform’s goal and the essential methodology that needs to be put in place to support current and future operational needs.

This topic is a continuation of a past Naval Research Program study. It was conducted by our research team in FY20 for Initial Research Estimate Form NPS-20-N313-A under “Data Strategies in Support of the Naval Operational Architecture.” Our present study applied a data strategy designed in the previous FY20 study to a “digital mission command” application suite. “Digital mission command” requires speed in Special Operations Forces’ (SOF) acquisition of situational awareness. SOF architecture must support requirements in the highly dynamic battlespace. It is not possible to accomplish such a goal unless a developed platform is highly adaptive due to superior understanding of the meaning of the surrounding mission and environmental events.

The methodology of our research study was designed to be capable of changing the behavior of the platforms to modernize “as is” command and control legacy approach based on past operational requirements. Our methodology follows best practices following the evolution of data, which follows the Data à Information à Knowledge à Understanding pipeline. Our research methodology provided analysis of all four phases and what is required to support maturing data in each of them.

The platform’s behavior must be advanced for two reasons: (1) A need to support the new concept behind “Command & Control” tokened as “digital mission command,” and (2) To be cognizant of a decade-long revolution in information technologies, which touches critical technology areas such as cloud technologies, universal storage platforms, and a number of open-source computing frameworks with high levels of adoption.

Findings and Conclusions
Our findings from a “data” step are evolving since FY21 from the earlier study of a data strategy for Naval Operational Architecture. The idea of a universal storage layer as a pillar for a variety of highly adopted computational frameworks is proven via ongoing investments, which now include Lockheed Martin Ventures. Our research team believes a realization from technology-savvy innovators is a great benefit to the unification of the “structured” in the over-the-cloud storage layer. A concept of structured multi-modal data integrated in a universal storage with clouds via containerization and virtualization technologies is a testament to the quality of our research. It proves that our finding regarding investment into the Data Lakes or Data Warehouses in the clouds is viewed by some experts as highly risky due to a steep “pay-as-you-go” pricing structure. A primary need for enabling infrastructure to be cost-affordable is the pivot behind DoD-focused ventures supporting higher-level constructed layers, attempting to escape escalating prices of cloud vendors.
Our research team concluded it is unfeasible to avoid ontologies and their integration with the data to leap to the “information” step in the data enrichment paradigm. Our conclusion is that the process of interpretation of ontologies into the ontological types with an idea of coupling ontological types with data is a streamlined paradigm with a better return on investment. We also concluded that there will be no single “upper ontology.” The world requires both a “realistic,” the way things are, approach, and a descriptive approach with the presence of conflicting hypotheses. Our ontology should support a reconciliation capability as opposed to taking sides with what, at the moment, is empirical truth. The world is more complex than a simplistic snapshot supported by the “realists.”

Our short-term implications convinced us of a high-payoff value by focusing on situational awareness with the goal to provide “contextual adaptation” capability. We feel combining the power of dynamic events of the world states with static objects, which describe the world, will let us discover the dynamics of world concepts. Our long-term implications are focused on defining a method of connecting graph data models’ events and objects in time and space to ensure they are concurrently summarized. This requires acquisition of building an aggregation engine that embeds data graph models and other modalities into a multi-dimensional multi-hierarchical cube.

Our findings and conclusions will improve the operational situation, including decision-making. The Naval Postgraduate School research team, per direction from the topic sponsor, LCDR Christian Brown, had a discussion with the Chief Technology Officer at NAVSPECWARCOM in regard to our recommendations on which technologies need to get adopted and which technologies need to be implemented. We were told such development only takes place in the Joint Artificial Intelligence Center (JAIC). We were promised to be introduced to the person in charge of AI stack to present our recommendations on the research, development, and acquisition of AI technologies. We will be reporting to the Naval Research Program on future developments after introduction to JAIC occurs.

**Recommendations for Further Research**

Additional research study should be guided by the task list presented below:

1. Develop a Graph Basic Linear Algebra Subprograms Application Programming Interface layer over multi-dimensional array storage.
2. Develop a Dynamic View Management layer that persists in a multi-dimensional array storage.
3. Integrate Natural Language Processing parsing/interpretation with a graph data model that persists in a multi-dimensional storage.
4. Develop a rule-based “semantic matching” approach between events and objects/entities for the purpose of “aggregation/summarization of graphs and non-graphs” using a generic function.
5. Implement an aggregation/summarization multi-dimensional multi-hierarchical engine capable of imbedding event graph data models and any non-graph data (including Point Cloud and multimedia) integrated with multi-dimensional array storage.
NPS-21-N113-B: Mapping and Analyzing NSW’s Blue Network to Leverage Insights for a Competitive World

**Researchers:** Dr. Sean Everton, Dr. Daniel Cunningham, and Mr. Christopher Callaghan

**Student Participation:** No students participated in this research project.

**Project Summary**
This study’s purpose is to examine Naval Special Warfare Command’s (NAVSPECWARCOM) “blue network” and evaluate its structural strengths and weaknesses, as well as provide recommendations as to how the command can improve its ability to leverage its network and draw insights from it. This paper examines this topic from a social network perspective on social capital. Guided by extant social network research, it maps and analyzes the network’s structural patterns and assesses the extent to which it has access to critical resources and expertise from outside networks (e.g., academic and private industry).

It finds that both close personal and colleague relations contribute substantially to regular communication patterns among personnel. Blue network members tend to form communication clusters as well, which can permit information and resources to transmit efficiently across them, especially in its relatively decentralized form. In fact, the command can rely on many network members to gain access to capital within the structure rather than depend heavily on a few well-connected individuals. However, about a quarter of respondents do not communicate regularly with the command, which indicates that capital may not reach the command. Furthermore, the type of capital to which the network has access varies. While it appears relatively strong in technology-based areas (e.g., innovation and artificial intelligence [AI]), it can make improvements in key substantive areas pertaining to great power competition (GPC), such as cultural and language expertise.

This paper offers two broad categories of recommendations: practices and information collection and storage procedures. Recommendations include maintaining an entrepreneurial mentality but improving formal communication, facilitating the creation of “short-cuts” among affiliated institutions, tasking personnel to target key resource gaps, immediately establishing contacts with experts in key areas, collecting blue network and resource data, and leveraging information systems for information storage.

**Keywords:** Naval Special Warfare Command, NAVSPECWARCOM, social network analysis, SNA, social capital, blue networks, resource generators, exponential random graph models, ERGMs, great power competition, GPC, informal networks, multilevel networks, social processes, emerging technologies

**Background**
Because it is critical for NAVSPECWARCOM to maintain a comparative advantage with foreign adversaries in key topics, such as strategic competition, advanced technologies (e.g., AI and robotics), and other subject-matter domains (e.g., culture awareness in key countries, foreign languages, and licit and illicit social networks), it needs to understand itself and assess the extent to which it is acquiring knowledge and resources from experts in key domains. This analysis provides the command with a better understanding of its blue network’s layout, much like a topographical map in any operating environment, and offers a glimpse into how personnel interact and communicate with one another.
Moreover, it identifies the resources and expertise to which the blue network has substantial access, as well as highlights gaps in its knowledge base, to help the command allocate personnel to reach its goals of operating effectively in future operating environments.

This paper takes a social network perspective on social capital and seeks to identify the social processes—the ways by which ties form—that underlie the blue network’s communication patterns. It leverages complete roster social network questionnaires that capture multiplex data (i.e., communication, personal, and colleague) among blue network personnel. It administers a second questionnaire to collect data about personnel’s access to non-NAVSPECWARCOM individuals (e.g., private sector and academia) who could offer capital to support the command. Following Van Der Gaag’s and Snijders’ (2005) work on “Resource Generators,” this paper outlined 67 resource items that the command thought were desirable to meet its objectives.

Our analysis draws on both descriptive statistics and social network models to examine how the blue network functions and formed in terms of social capital. An important aspect of social capital pertains to one’s level of analysis. Consequently, this analysis tested several hypotheses pertaining to several prominent theoretical mechanisms about tie formation that can occur at the individual and cluster levels, as well as between multiple types of ties (e.g., colleague and communication ties). To test the hypotheses, this paper leveraged exponential random graph models (ERGMs) to model social processes underlying NAVSPECWARCOM’s communication network. This model class offer researchers a means to examine various multilevel social processes that help give rise to a network’s observed patterns at the macro level (Lusher et al., 2013; Monge & Contractor, 2003; Robins, 2015).

**Findings and Conclusions**

This paper uncovered empirical support for several, but not all, of the hypotheses. Using ERGMs, it found that blue network personnel tend to form communication clusters that can permit information and resources to transmit efficiently across them, especially in a decentralized form. Also, it discovered that hubs do not dominate the network, which suggests the command can rely on many individuals to gain access to capital within the structure rather than depend on a few well-connected individuals. In general, it appears that personnel are well-connected with many other blue network members with whom they can share information and resources. However, only 79% of the respondents communicate with their command on a weekly or monthly basis, which indicates that while capital could flow among personnel in an informal manner, it may not always reach the command level in a formal, systematic way.

Additionally, this analysis found that both personal and colleague relations contribute substantially to regular communication patterns among personnel. As extant literature demonstrates, understanding informal relations like these can offer valuable insight into an organization and its ability to acquire capital (Eisenberg et al., 2015; Krackhardt & Hanson, 1993; Kratzer et al., 2005; Molina-Morales & Martinez-Fernandez, 2010; Obstfeld, 2005; Romzek et al., 2012). While it is possible that NAVSPECWARCOM collects and stores information about who served with whom (i.e., colleagues), it is likely unaware of the role that personal ties, which can include friendships that take place outside of official business, play in the formation of communication interactions that it can leverage for capital and meet its objectives. Similarly, this analysis found that being co-located at the same type of institution can improve the chances that individuals will communicate.
While the blue network may possess advantageous structural properties, the type of capital to which it may have access varies depending on the topic. Based on the available data, the blue network is relatively strong in areas pertaining to technology-based activities, such as innovation, AI, unmanned systems, and access to technology hubs like Silicon Valley. However, the blue network lacks potential access to capital in many key substantive areas pertaining to GPC for which it should account in the future, including issues pertaining to shifting geopolitical, socio-economic (e.g., instability and shifting demographics), and technological (e.g., biometrics) trends, as well as the convergence of “future trends” (e.g., extremism, nation-states, changing battlefield) (Mattis, 2018; United States Special Operations Command [USSOCOM], 2019).

This paper offers two broad categories of recommendations: practices and information collection and storage procedures. Recommendations include maintaining entrepreneurial mentality but improving formal communication, facilitating the creation of “short-cuts” among affiliated institutions, tasking personnel to target key resource gaps, immediately establishing contacts with experts in key areas, collecting blue network and resource data, and leveraging information systems for information storage.

**Recommendations for Further Research**

This analysis provides a useful, yet static, depiction of Naval Special Warfare Command’s blue network. The command should consider regularly and systematically collecting information about relationships among blue network personnel and their external contacts. Some data is relatively straightforward to capture, such as communication ties and personnel who worked closely at previous deployments (e.g., colleagues), whereas other data is a bit more intrusive and may have to be voluntary (e.g., personal ties). While this analysis leveraged questionnaires, the command could consider analyzing email exchanges (i.e., not content but who emails whom) to understand regular communication among personnel. Regardless of the approach, it is important to consider multiple types of relations because some ties, like “personal” and “colleagues” in this study, may help explain the formation of others (e.g., communication). By collecting both network and resource data regularly, the command can understand more effectively its informal blue network and its ability to acquire capital even as personnel move from one position to another.

Future social network research on blue network mapping should consider addressing social capital in at least two other contexts. The first is to expand research to include the broader U.S. Navy social system in which personnel seek to enhance the branch’s ability to access resources and expertise. Identifying relationships between key naval commands engaged with one another can enable a branch-wide efforts to address issues pertaining to great power competition (GPC). The second context is to map and analyze relations among the branches in joint settings in which access to resources and expertise are key, particularly within a GPC and “future operating environment” contexts.

**References**


N8 - INTEGRATION OF CAPABILITIES & RESOURCES

NPS-21-N031-A: Applying Design of Experiments to Improve Campaign Analysis with the Synthetic Theater Operations Research Model

Researchers: Dr. Susan Sanchez, Dr. Thomas Lucas, Ms. Mary McDonald, and Maj Stephen Upton USMC Ret.
Student Participation: No students participated in this research project.

Project Summary
Navy leadership is interested in initiatives that can potentially increase the responsiveness of campaign analysis. Simulation-based campaign analysis is used to measure risk for investment options in how best to equip, organize, supply, maintain, train, and employ our naval forces. The Synthetic Theater Operations Research Model (STORM) is a stochastic simulation model used to support campaign analysis by the U.S. Navy, Marine Corps, and Air Force. Building, testing, running, and analyzing campaign scenarios in STORM is a complex, time-consuming process. A simulated campaign may span months, involve scores of ships and battalions, hundreds of aircraft and installations, all executing thousands of interconnected missions involving numerous events in time and space. Creating, testing, and approving the inputs for a single design point (DP) requires a significant investment in analysts’ time and computing resources. Consequently, there are limits on the number of DPs that can be produced, executed, and analyzed during a study’s timeframe.
This research assesses state-of-the-art methods in computational experimental design and other technologies with a goal of improving the timeliness, breadth, and robustness of future Navy studies using STORM. The long-term objectives are to apply cutting-edge sequential and adaptive design of experiment (DOE) methods in the selection of DPs to minimize the number of modeling runs required for meaningful comparisons, and to develop an understanding of the conditions in which these sophisticated designs are useful in comparison to traditional baseline and excursion modeling. The DOE methods should ensure control over variation so that insights gained through analysis are meaningful, timely, and defensible. In this initial phase, we present three approaches (sequential, comparative, and focused) and describe opportunities for their use on STORM scenarios that are either unclassified, mature classified scenarios, or working scenarios. We recommend applying a mix of all three methodologies to a classified scenario in the future.

Keywords: campaign analysis, data science, design of experiments, modeling, simulation, Synthetic Theater Operations Research Model, STORM

Background
Navy leadership is interested in initiatives that can potentially increase the responsiveness and value of campaign analysis. One promising approach is to use recent advances in DOE for high-dimensional computational models. The Simulation Experiments & Efficient Designs (SEED) Center for Data Farming at the Naval Postgraduate School (NPS) is a leader in advancing the collaborative development and use of simulation experiments and efficient designs to provide decision makers with timely insights on complex systems and operations. This research builds on a previous partnership between the Assessment Division [N81] of the Office of the Chief of Naval Operations (OPNAV) and the SEED Center for Data Farming in exploring STORM, which resulted in four student theses (Bickel, 2014; Seymour, 2014; Cobbs, 2016; King, 2018). A suite of tools for post-processing STORM data, along with managerial approaches and controls improvements to the study process, are described in Morgan et al. (2018).

The overarching research objectives are (i) to apply DOE methods in the selection and creation of DPs to minimize the number of STORM runs required for meaningful comparisons and (ii) to determine how to best use DOE methods to complement traditional baseline and excursion modeling.

The NPS team has combined decades of experience in both the theory and application of DOE to simulation studies. This includes the use of single-stage designs such as nearly orthogonal Latin hypercubes (Cioppa & Lucas, 2007; Hernandez et al., 2012), nearly orthogonal-and-balanced designs (Vieira et al., 2013), and frequency-based designs (Sanchez & Sanchez, 2019). These are very efficient, allowing analysts to investigate the impacts of hundreds of factors on simulation responses when a brute force approach is impossible. Sequential designs (Duan et al., 2017) and adaptive sequential designs (Sanchez et al., 2010; Erickson et al., 2021) can provide further efficiencies.

Design points are the combinations of factor settings for a particular simulation run. There are two types of design points for STORM studies: major DPs and minor DPs. Major DPs, such as those that reflect qualitatively different operational policies or different command and control plans, require a significant investment in developers’ and analysts’ time and effort. There are limits on the number of these major DPs that can be produced, executed, and analyzed during a study’s timeframe. Minor DPs involve
changes to quantitative inputs that are more straightforward to articulate and implement. For example, minor DPs might vary quantitative model inputs over specified ranges of interest. The computing effort required is often the limitation on exploring minor DPs.

Most of the SEED Center’s earlier work on STORM involved minor DPs and unclassified scenarios. However, the major DPs are of most interest to OPNAV N81 because of the extensive development time and cost required.

**Findings and Conclusions**

We propose that different approaches be applied at different times during a STORM study process.

A sequential approach could suggest future major DPs that involve inputs that are difficult to change, such as those that reflect qualitatively different operational policies or command and control plans. Determination of specific DPs to instantiate would be driven by needs/expertise/questions of N81 following deep dives into analysis and interpretation of previous major DPs. The DOE comprised of these new DPs will be very efficient (i.e., a very limited number will be created).

A comparative approach can be used to aid in verification and validation efforts and to help identify reasonable factor ranges or levels. This involves structured parameter variation for (some of) the easier-to-change, quantitative factors and thresholds. It can provide guidance on factor ranges and combinations for which STORM does or does not produce credible output. If a working scenario is selected, comparisons can be used within the sequential approach: iterating over smaller DOEs can assist in verification/validation efforts during the (longer process of) creation of a new major DP.

A focused approach involving one or more existing DPs could provide guidance on appropriate metrics, factor ranges or levels, or sensitivities to components or data provided by others. This does not involve creation of new major DPs. Analysis of experiments involving an existing major DP may help reveal how much variation in other DPs is worth exploring. For example, DOE could be used to efficiently identify ranges for selected inputs for which the STORM output is relatively stable, or ranges beyond which the STORM output is not credible. Other features or components to explore would be guided by general needs N81 has identified. For example, one challenge in a long-term study is the need to wait for certain types of data (perhaps coming from higher classification levels) before doing analysis. With a focused approach, we could explore what type(s) of experiments might provide useful intermediate information regarding STORM’s sensitivity to components where data are uncertain or at a classification level above SECRET. These methods or lessons learned might transfer over to working scenarios, so OPNAV N81 could gain insights from experiments conducted while waiting for input from others on certain components of the STORM database.

These approaches should be applied to a classified study so we can collectively learn how best to use state-of-the-art DOE methods to complement traditional baseline and excursion modeling. As COVID-related hurdles prevented classified work, this project was cut short early in 2021. Follow-on research involves a classified STORM scenario.

**Recommendations for Further Research**

Large-scale simulation models inform many important decisions within the Department of Defense.
Creating or modifying these models often requires substantial time and effort from teams of developers and analysts in close consultation with subject matter experts. Recent breakthroughs in large-scale simulation experiments have allowed analysts and decision makers to gain a much broader and deeper understanding of the model behavior while avoiding the so-called “curse of dimensionality” that makes brute force model exploration impossible. In a nutshell, well-designed experiments consist of carefully chosen combinations of model inputs, called design points. The Naval Postgraduate School’s Simulation Experiments & Efficient Designs (SEED) Center for Data Farming is a recognized leader in advancing the theory and application of large-scale simulation experiments. Data farming is a metaphor for growing data from computational experiments.

Further research is needed to address the needs of senior leaders who use models (such as campaign models) where some of the design points are difficult to instantiate. For example, some design points might reflect qualitatively different operational policies or command and control plans, and consequently have a long lead time and high cost. A better understanding of how designed experimentation can complement the traditional baseline and excursion modeling process merits further research.

References
**Project Summary**
This project is part of a recent line of effort supported by the Office of the Chief of Naval Operations (OPNAV) intended to clarify the structure of a suite of performance/pricing models (P/PMs) that has been used since 2004 to inform the Navy’s aviation budgeting process. Specifically, this project focused on a particular P/PM called the Engine Depot Readiness Assessment Model (EDRAM) that is used to help plan depot-level maintenance for aircraft engines, with the goal of identifying the inputs to the EDRAM that most strongly relate to the number of ready for issue (RFI) engines predicted by the model. A designed experiment was used to assess the dependence of the number of RFI engines on maintenance turn-around time (TAT). Our primary finding was that, in the context of the EDRAM, TAT is only weakly related to the number of RFI engines.

**Keywords:** Naval Aviation Enterprise, maintenance, budget, optimization, Program Objective Memorandum, Engine Depot Readiness Assessment Model, EDRAM

**Background**
The EDRAM is part of a suite of P/PMs that has been in use by the Naval Aviation Enterprise since 2004 to inform funding decisions and predict the effects of funding allocations on readiness. In response to observed declines in readiness over the past decade despite funding increases and the use of P/PMs, OPNAV N81 is currently supporting efforts to clarify the structure of these models and how they relate to each other. This line of work began with Ellis (2019), who investigated and mapped the relationships between the various P/PM modules. Subsequently, Thaw (2020) developed a regression model for analyzing the relationships between the outputs of the Flying Hour Program module and readiness. This analysis methodology was refined and extended to other modules by Luerman (2020).

The primary goal of this research effort was to clarify the dependence between the inputs to the EDRAM and its outputs that relate to readiness. Specifically, we focused on finding inputs that drive the number of RFI engines that the model predicts will be available in each future fiscal year. Once such inputs are found, a designed experiment was used to assess the sensitivity of the predicted number of RFI engines to changes in the inputs, which in turn can suggest how resources for maintenance or process improvement should be allocated to have the largest impact on readiness. A major difficulty that had to be handled in this study was that the EDRAM is essentially a “black box,” in the sense that the relationships between its various inputs are such that there is no simple closed-form formula for how inputs are translated into outputs.

**Findings and Conclusions**
Based on an extensive review of existing documentation and prior studies that included the EDRAM in the context of the full suite of P/PMs, the depot TATs associated with the various engine types handled by the EDRAM were identified as an input variable of interest. For a given depot, engine type/model/series (TMS), and maintenance event, the TAT is the number of days that the associated engine spends as
“Work in Progress” at that depot when it undergoes that type of maintenance event. Reductions in a particular TAT can be interpreted as corresponding to improvements in maintenance processes at a particular depot, and an understanding of which TATs are most strongly related to readiness can inform how process improvement resources should be allocated.

We designed a numerical experiment to systematically vary the different TATs, so that the TATs that most strongly affect the predicted number of RFI engines could be determined. Since one of the main motivations for the study was declines in readiness associated with carrier air wings (CVWs), we elected to focus our experimental design on the TMSs associated with CVWs. This experiment revealed that the output variable of interest (i.e., the number of RFI engines) is largely insensitive to changes in TAT. This result was unexpected and indicates that other factors in the EDRAM may be limiting the effect that TAT can have on the number of RFI engines.

**Recommendations for Further Research**
A major task for further research is to continue exploring the Engine Depot Readiness Assessment Model (EDRAM) inputs to determine which, if any, are useful for experimentation. This will help to clarify how the EDRAM works, and in turn, how its underlying assumptions may affect its outputs. Another avenue for further research is to apply the experimental design methodology to other performance/pricing models.

**References**

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**NPS-21-N117-A: Optimization of Airframe Depot Readiness Assessment Model (ADRAM)**

**Researchers:** Dr. Douglas MacKinnon and Dr. Jefferson Huang

**Student Participation:** LCDR Ian Henry USN

**Project Summary**
The naval aviation enterprise (NAE) is tasked with providing sufficient numbers of aircraft to meet readiness and operational surge requirements. This study seeks to improve readiness as defined by the number of mission-capable aircraft available for operational tasking. Our research is focused on the output of the Aviation Depot Readiness Availability Model (ADRAM) and seeks to inform Senior Leaders with regard to funding decisions about aircraft maintenance. Our hope is to reduce the risk of decreased aircraft readiness as well as explore the available trade space and implications of potential alternatives, revealing some practical outcomes. This project also seeks to optimize ADRAM’s ability to balance readiness with cost.
The far-reaching implications of programmatic decisions concerning maintaining aircraft airframes through the examination of “operational availability” is a complex problem that requires exploration.

Through our examination of ADRAM output over numerous maintenance events; many depots; and many types, models, and series (T/M/S) of aircraft, we found that ADRAM does not produce the most efficient and effective set of maintenance events required to meet a specific readiness goal (or to implement a decrease in funding). There are two basic reasons for this observation: some of the model’s solution algorithms do not appear consistent with current practices, while other algorithms reflect current practices that are likely to be suboptimal. In particular, we observe that ADRAM assumes that the most expensive tasks are the first to be deferred. This does not necessarily minimize the impact of the delay on readiness. Also, ADRAM assumes that “level-loading” of maintenance tasks occurs across facilities. This may be consistent with current practices but does not necessarily allocate events to the most efficient facilities. Furthermore, ADRAM assumes “fair-sharing” of budget cuts across facilities. This does not necessarily defer events away from the least efficient facilities.

**Keywords:** optimization, design of experiments, DOE, Program Objective Memorandum, POM, naval aviation enterprise, NAE, budget, Aviation Depot Readiness Availability Model, ADRAM

**Background**
OPNAV N81’s assessment of the Program Objective Memorandum (POM) with operating appropriations of $50 million or more is based upon the accreditation of models used during the budgeting phase by Navy Resource Sponsors. These models, called performance/pricing models (P/PM), are analytical tools used to relate budgeted costs to observed performance levels. However, during recent POM development cycles, the accuracy of these models has come into question, and N81 has been tasked with identifying the potential causes. N81 is seeking to determine if current level-of-effort thresholds are sufficient to accurately determine the appropriate level of accreditation, the cause of variance between P/PM-informed budget projections and subsequent execution, the accuracy of external P/PM inputs, and internal P/PM algorithms and cost estimation relationships. This inquiry supports this effort and focuses on the subset of models that will carry out timely and reliable Operational and Support cost estimates for NAE’s aircraft at their early stages of conceptual design, despite the lack of actual data from utilization and support life cycle stages. Their models’ output is validated against Cost Per Flight Hour data of existing aircraft. Actual historic data is used to inform future parametric modeling, the application of which will support the sponsor’s goal of improving aviation readiness through improved funding decisions regarding aircraft procurement, budgeting, and future force structure planning, including decisions related to large-scale aircraft modifications and upgrades.

**Findings and Conclusions**
This effort sought to address the problem of optimizing funding for carrier-based aircraft by leveraging the pre-existing model referred to as ADRAM. We began by analyzing previous research to understand this model (Ellis, 2019; Luerman, 2020; Thaw, 2020). We approached ADRAM experimentation by applying differing levels of specific variables for many different aircraft, two separate maintenance events, and aviation depot locations. The eventual variable selected to serve as a surrogate for changes in levels of funding was Turn Around Time (TAT), as this variable is implemented in ADRAM for all carrier air wing (CVW) aircraft.
We began to develop and execute a design of experiments (DOE) (Durakovik, 2017; Sanchez, 2020) and through numerous sets of model runs, we observed little change in Operational Availability (Ao).
Specifically, we analyzed every combination of T/M/S, two maintenance events, and different depot locations, yet only E-2D aircraft appeared to reflect anticipated changes in aircraft availability from ADRAM output. Specifically, the E-2D “% of Goal” of Ao behaved as expected. As TAT was decreased, “% of Goal” increased for each year observed across the future year defense program (FYDP). Our efforts suggest that counterintuitive output appears to occur when modeling numerous combinations of maintenance events, numerous T/M/S, and aviation depots, and that other variables may act as limiting factors. Yet, for the E-2D, we note that modeling reductions to TAT for planned maintenance interval number 2 (PMI 2) resulted in improvements to “% to Goal” across the FYDP, and ultimately this analysis indicates where to shift funding—our original goal. Specifically, our output indicates that funding to reduce TAT for PMI 2, rather than PMI 1, should be expended as this results in improving Ao. Finally, ADRAM defers maintenance for each T/M/S of aircraft with the smallest excess availability. In general, this does not efficiently control excess inventory and is unlikely to reflect actual practice. Further exploration of ADRAM may reveal how it may best be used to help understand aviation readiness.

Recommendations for Further Research
Future research should be considered to build upon the results from the current study to enhance the Navy’s operational available aircraft through the use of the Aviation Depot Readiness Availability Model (ADRAM). ADRAM’s efficacy could be further determined by continuing to develop design of experiments to search and analyze other variables using enhancements such as Nearly Orthogonal Hyper Cube designs (Sanchez et al., 2020). This effort may also be used to examine other performance/pricing models (CNO, 2021).

References
NPS-21-N173-A: VLS Missile Mix, Firing Policy, and Deterrence Against Red Salvos

Researchers: Dr. Michael Atkinson, Dr. Moshe Kress, and Dr. Javier Salmeron-Medrano
Student Participation: ENS Steel Templin USN

Project Summary
The U.S. Navy (USN) utilizes the Vertical Launch System (VLS) to store and launch both their offensive and defensive missiles. The number of VLS silos on a given ship is fixed. Thus, in order to maximize offensive capability, the USN wishes to minimize the number of interceptors to combat incoming, anti-surface missiles. Current firing policies may be overly conservative and expend too many interceptors per incoming threat, which results in a substantial fraction of VLS silos dedicated to defensive missiles. Decision makers need an analysis tool to explore the tradeoff between missile consumption and probability of raid annihilation (PRA) for various firing policies; they would also benefit from a prescriptive algorithm to help inform missile expenditure. This project provides a model to optimize VLS firing policy using multiple interceptor types while accounting for range limitations, travel time, multi-interceptor salvos, battle damage assessment, and range-dependent probability of kill. Additionally, the project derives analytical results for the optimal allocation of interceptors in the single interceptor case, which in turn generates insight into how to structure sequential salvos.

Keywords: firing theory, salvo model, battle damage assessment

Background
Modern USN surface ships and submarines are outfitted with a common launching “mount” known as the VLS. VLS allows for missile compatibility regardless of the specific platform that carries them. Ships can be outfitted to fit mission needs and can utilize future missiles that will be developed later in the ship’s life-cycle. VLS inventory is divided into separate mission sets such as anti-submarine, anti-surface, land-attack (commonly known as “strike”), integrated air and missile defense (IAMD), ballistic missile defense, etc.

Depletion of IAMD loadouts will result in a total degradation of combat effectiveness as a ship is rendered defenseless and—assuming it survives—must return to port to reload. This VLS replenishment is a multi-day voyage to and from a shore installation with additional time potentially spent waiting in port if the reloading infrastructure is preoccupied with other ships. During this duration, the vessel is not on station and therefore is not conducting any missions.

This project focuses on the employment of defensive (counterfire) interceptors, which falls under the IAMD mission set. Traditionally, a USN ship’s captain decides how to deploy and employ missiles against incoming threats, and this firing policy is usually the same for all threat types. A firing sequence consists of a series of salvos fired at the incoming threat. Each salvo is a collection of interceptors that may include duplicates of a single interceptor type or a combination of different types of interceptors. After each salvo, the blue (defending) force performs battle damage assessment (BDA) to determine the outcome of the salvo. There is a “cost” to fire each interceptor, whether financial or in opportunity.
Current policies such as shoot-look-shoot do not consider situation specifics such as detection range, inventory, or threat. We focus on improving the engaging sequence by exploring policies regarding the interceptor composition of each salvo relevant to a specific situation. Our model is a heuristic based on simplifying assumptions that generates effective heterogeneous firing sequences against a given threat. It factors in constraints of minimum and maximum interceptor ranges, interceptor transition time between launch and impact, range-dependent probability of kill, BDA, and time to conduct BDA.

First, we analyze one salvo to compute the probable impact point (PIP) of each interceptor. The PIP is the input to range-dependent single-shot probability of kill (SSPK). We next string together several salvos to construct a firing sequence. Aggregating the SSPKs across all interceptors and salvos yields the PRA.

To determine the best firing sequence, we develop a recursive algorithm to generate all feasible firing sequences. This recursion provides a heuristic approximation for the lowest-cost sequence that surpasses a user-specified PRA threshold, Q.

In addition to the general model that includes heterogeneous mixes of interceptors, we explore a simplified case with homogeneous interceptors distributed across multiple salvos. This portion of the project does not include BDA delay or range-dependent SSPK.

**Findings and Conclusions**

The key finding of this analysis is that sequences should be structured such that they are monotonically non-decreasing with salvo index. If the optimal sequence—from an expected cost perspective—has two interceptors in a salvo, all subsequent salvos will have two or more interceptors.

Additional findings for the homogeneous case include: (a) expected cost decreases as the number of salvo firing opportunities increases; (b) the optimal fraction of interceptors allocated to each salvo does not depend on SSPK and instead depends on the number of salvo opportunities and PRA threshold Q (this implies SSPK only impacts the number of interceptors required, not the optimal structure of sequence); and, (c) above a certain SSPK, the optimal firing sequence has one interceptor in all salvos except the last one, which fires the remaining interceptors. This suggests that a sufficiently high SSPK simplifies allocation as only the final salvo needs adjustment.

Our work suggests that the key to decreasing the expected number of interceptors expended per threat is maximizing the number of salvo opportunities in a firing sequence. This can be done through early detection—improving detection and classification range—and having the requisite interceptors to match this expanded capability. Firing opportunities can also be increased through improved BDA time and having high-velocity interceptors with improved minimum range. After maximizing salvo opportunities, the next important aspect is interceptor allocation. We prove that salvos should be monotonic, non-decreasing in size for the homogeneous case; however, our preliminary results show this broadly holds for the heterogeneous case as well. Finally, our work demonstrates that each interceptor type plays a role in generating optimal sequences and that model inputs of detection range and BDA delay have second-order effects on the results.
Ultimately, optimal firing sequences are dependent on the threat type, interceptor availability, and detection range. Exploring the interaction between these factors while considering different interceptor salvos is a complicated task, but our model provides a streamlined approach to modify parameters and generate near-optimal sequences. Examples of how our model can be used include preemptively deriving a firing policy for a given threat scenario, evaluating new or upgraded interceptors, and feeding into a loadout planner to provide end-to-end optimization from logistics to firing.

**Recommendations for Further Research**

The main next step would be to incorporate soft-kill interceptors into our model. Soft-kill systems are known for having much lower battle-damage assessment (BDA) quality than hard-kill ones. For soft-kill, false negatives would be the primary concern. A false negative occurs when blue believes it has not killed the incoming threat despite already having a successful interception. False negatives can lead to wasteful expenditure of interceptors. False-positive would have serious implications for firing policy but such assessment is very unlikely; a missile traveling at high speed towards a ship is hard to mistake as being killed.

The difficulty with soft-kill analysis is there are many different types of soft measures and each has a drastically different mechanism of successfully scoring a “kill.” Some of these methods include jamming, directed energy, chaff and decoys. The first three provide an instantaneous effect when “deployed.” Chaff is a one-time expenditure but can be applied to multiple threats. While jamming and directed energy “impact” instantaneously, they require a certain amount of time on target, after which jamming leads to a soft-kill while energy weapons are more akin to a hard-kill. Decoys are the only non-instantaneous soft-kill measure, as they require transition to the target, after which it remains active for some defined time parallel to additional salvos.

Another extension would be for multiple threats. We focus on a single threat to better explore how the salvos should be structured. Many real-world scenarios face multiple simultaneous threat groupings. This is magnified with the advent of loitering munitions.

Generalizing to multiple threats would require insight from subject matter experts on what simplifying assumptions can be made. The main considerations are inventory limitations; channel limitation, as a finite amount of active or semi-active seekers that can be airborne at a time; and expenditures such as chaff that effect multiple threats at once. One approach to multiple threats could use our model to generate a diverse collection of sequences for each threat, and then feed those sequences into an optimizer with the appropriate constraints applied.

A last extension could re-examine our assumption about firing a salvo as early as possible. Our model provides near optimal-solutions, but better solutions could exist by optimizing the firing time of each salvo. This would significantly increase the computational complexity of the problem. One approach to incorporate timing into the model in a computational tractable way would be to introduce a “waiting” action into the design. The waiting action would be for a set length of time (e.g., wait 10 seconds before firing a salvo) that an operator could adjust.
NPS-21-N180-A: Warfighting Readiness PESTONI Study

**Researchers:** Dr. Bryan O’Halloran and Mr. Gary Parker  
**Student Participation:** Mr. Seth Bourn CIV

**Project Summary**  
The acquisition process for U.S. military systems has been developed and extended over its history to procure military capable systems. Adversary militaries from around the world are also acquiring systems with the intent to create opposition to those procured by the U.S. military. This ongoing process results in a canvas of capabilities and specifically the capability gaps between the U.S. military and its adversaries. As such, the identified capability gaps are a focus area for acquiring military systems. Programs of record (PoRs) are an organizational avenue for addressing known capability gaps. However, underperforming PoRs are a known challenge in this process; underperforming PoRs are unable to deliver the expected capabilities, which increases the risk of an underperforming U.S. military that lacks the necessary capabilities to compete with its adversaries.

The result of this study is a risk management framework used to assess degradation indicators. More specifically, the risk management approach is proposed to plan for, identify, analyze, handle, and monitor degradation indicators. Such an approach is designed for the total management of risk as it relates to capability deficiencies.

**Keywords:** capabilities assessment, programs of record, PoRs, PESTONI, modeling and simulation, data analysis, program management

**Background**  
The systems development process is a long and arduous undertaking, even for the most experienced organizations. Often the process takes many years from start to finish. While the intent is to design the system for a specific set of capabilities, not all capabilities are ultimately realized within the system. The reasons for these deficiencies represent the intent of this study. To exacerbate the issue, PoRs occasionally do not complete the development process, leading to a complete loss of the expected set of capabilities. In the modern warfighting paradigm, this loss of capability can be catastrophic to a military. As such, there is a need to understand when PoRs will not realize their set of capabilities.

**Findings and Conclusions**  
In this project, a PoR capability impact management framework is proposed with a specific goal to manage capability degradation indicators within PoRs. The proposed framework is derived from the risk management approach used in the Department of Defense (DoD) (Baldwin, 2015). A risk management approach is used to ensure that there is total ownership over a system’s capability. More specifically, any deficiency in capability will be tracked until it is resolved. The risk management concept used in the DoD manages these deficiencies as “risks.” The process manages risks cradle-to-grave to enforce total ownership of the risk as it relates to deficiencies in capability.

The steps of the proposed risk management framework include planning, identifying, analyzing, handling, and monitoring (Baldwin, 2015).
Each step in the process answers a unique question, which is shown below. The process itself is iterative where risks are often analyzed and then reanalyzed due to changes within the program or in system.

**Planning:** What is the process used for capability impact management?
**Identifying:** What are the degradation indicators that will eventually impact capability?
**Analyzing:** What is the probability a degradation indicator will impact capability and how badly will it impact capability?
**Handling:** How should degradation indicators be dealt with (e.g., mitigate, accept, avoid, or transfer)?
**Monitoring:** How are degradation indicators tracked and how does their risk change over time?

In addition to each step summarized above, a worksheet has been developed to guide the analyst through the steps of the process and to document results. Further details on the worksheet and each step is provided in the project final report.

A benefit to using a risk management framework is the accumulation of data over time. This lends toward the development of a quantitative model to relate degradation indicators with underperforming PoRs. After applying the framework to several PoRs, a corpus of risk management data will begin to develop. This data will highlight some of the predominate degradation indicators within PoRs and the consequence those have on the PoR. The data may also be useful for assessing programs with limited data. More specifically, PoRs with limited data can be assessed against risks identified from analogous programs. As such, data accumulated from this risk management approach should be retained for long-term use.

**Recommendations for Further Research**
A known limitation of this work was the limited program of record (PoR) data available. Data used in this project was gathered from internet sources; however, it was not obtained directly from the PoR. As a result, the data was very limited in size and depth. Follow-on work should focus on acquiring detailed PoR data and determining any impact to the proposed framework.

**References**
**NPS-21-N368-A: Optimizing Large Financial Portfolios**

**Researchers:** Dr. Jefferson Huang and Dr. Judith Hermis  
**Student Participation:** No students participated in this research project.

**Project Summary**  
This project addresses the question of how uncertainties in the budgeting process, such as those related to costs, scheduling, and performance, can be tractably accounted for in making funding decisions. We formulate and implement an optimization model based on finding funding allocations that minimize the conditional value-at-risk of the associated portfolio. The implementation is embedded in a dashboard that allows a decision-maker to interactively exercise the parameters associated with return-on-investment risk and budget risk. Major open research directions include studying how the model inputs related to returns on investment should be estimated and the kinds of behaviors that this and other portfolio optimization models incentivize.

**Keywords:** financial modeling, optimization, portfolio optimization, risk, budgeting, uncertainty

**Background**  
The Office of the Chief of Naval Operations N80E is responsible for providing fiscal analysis to support budget decisions and the defense of the Program Objective Memorandum. There are many sources of uncertainty in this process, including uncertainties in costs, scheduling, and the performance of procured systems. These uncertainties mean that for any given budgeting decision, there is some amount of risk in ending up with less-than-desirable outcomes. On the other hand, certain budgeting decisions carry less risk than others, and among those decisions with a given expected return on investment, those that carry less of a risk of adverse outcomes should be preferred.

As part of ongoing efforts to better account for uncertainty in the budgeting process, this project focused on how to do this in the context of decision problems that can be viewed as allocating investments to several different projects (i.e., portfolio optimization problems). Examples of such problems include deciding which weapons systems to procure, and how much money should be set aside for various appropriation categories. One approach to explicitly accounting for uncertainty and risk in portfolio optimization problems is to minimize the conditional value-at-risk (CVaR) of the portfolio. This approach has received a great deal of attention in the private sector and has attractive computational properties (Rockafellar & Uryasev, 2000). It generalizes more classical portfolio optimization models whose objective is simply to maximize the expected value of the portfolio’s return on investment. Such models are often referred to as being risk-neutral, in the sense that they simply optimize the average return without regard to the variability of the return. The CVaR objective includes a tuning parameter that allows the decision-maker to vary their level of risk-aversion, so that portfolios with a higher risk of adverse outcomes are penalized.

**Findings and Conclusions**  
In this project, we formulated and implemented a CVaR optimization model in the context of appropriation-level portfolio optimization, with additional constraints that capture salient features of this problem context.
For example, the model allows the benefits of a given investment in a particular fiscal year to be spread out over time and includes constraints on the chance with which the total ownership cost will be within the total obligation authority in each fiscal year. In addition to an implementation using Pyomo (Hart et al., 2011), we also developed and implemented a dashboard that facilitates the visualization of the portfolios that are recommended by the model and allows for interactive model excursions. Through this dashboard, a decision-maker can quickly see the impact of varying the risk-related model parameters on the recommended portfolios.

**Recommendations for Further Research**
A major direction for further research deals with how returns on investment should be quantified in the context of defense budgeting. While the model developed in this project can take such values as inputs, it does not explicitly provide guidance on what those values should be. Another important future research direction is in studying the kinds of behavior that the portfolio optimization model incentivizes, and if the incentivized behavior is undesirable, how the model should be modified to incentivize better decisions.

**References**

## N9 - WARFARE SYSTEMS


**Researchers:** Dr. Oleg Yakimenko  
**Student Participation:** Capt Seungwan Cho ROKA FORNATL and MAJ Joel Li RSAF FORNATL

**Project Summary**
This study assessed applicability and benefits of using a multispectral (MS) sensor (as opposed to or in addition to a standard electro-optical [EO] and/or infrared [IR] sensors) on board small unmanned aerial systems (sUAS) for enhancing accuracy and precision of object detection (identification), classification and tracking (DCT) that may contribute to a variety of downstream applications including threat detection, forensics, battle damage-assessment, and additional/alternative aid to navigation (ATON) in Global Positioning System (GPS)-degraded or GPS-denied environments. It also includes an assessment of the computer-vision and artificial intelligence algorithms to process the MS sensor output quickly and reliably. The overall conclusion is that the usage of multi-band MS sensors instead of EO or EO/IR sensors represents a feasible enhancement/alternative. Further assessment should include investigation of the effects of operating environment (including meteorological factors and sUAS mission parameters) to determine limitations of the MS-based DCT and ATON.
Keywords: small unmanned aerial systems, sUAS, multispectral, MS, MS sensor, unexploded ordinance detection, machine learning, Global Positioning System, GPS, GPS-denied navigation, navigational aid, feature extraction and matching, vision odometry

Background
These days, an integrated EO/IR sensor and its associated signal or image processing, tightly integrated in form and function, is a standard payload for manned and unmanned aerial systems (UAS) of Group 1 and higher. Specifically, Group 3–Group 5 UAS use numerous sensor technologies that span from ultraviolet to far infrared. EO/IR sensors are used to detect and identify targets, track moving targets, and assess threats from a distance and in challenging environmental conditions. Common applications of EO/IR systems include airborne homeland security, combat, patrol, surveillance, reconnaissance, and search and rescue programs.

For most gimbal pointing applications, including geo-referencing, the gimbal control system requires position data, which precludes a solution provided by Inertial Navigation System (INS) and requires a GPS-aided option. In order to operate in GPS-denied environments, which is becoming a growing concern as peer-state rivals continue to advance GPS spoofing and denial techniques, new technologies are being explored/developed. Particularly, Vision Navigation is considered to be one of the most rudimentary forms of navigation and involves building a database of terrain features or landmarks that can then be tracked by onboard sensors in order to calculate a vehicle’s position, velocity, and altitude to provide a precision, navigation, and timing (PNT) solution.

MS imagery is a relatively new technology. The difference compared to the EO and infrared IR sensors is that MS sensors capture reflected light/energy in the number of bands rather than in a single narrow band. Because MS and HS imaging captures information that cannot be seen with the human eye and presents a more data-rich mosaic for scientists, it has become a highly desired technology for applications within the remote-sensing realm. These applications include crop science, precision agriculture, mining and mineral exploration, petroleum exploration, ecology, disaster mitigation, and others. Typically, these applications are most efficiently done from the air.

The research questions addressed in this study included the following:
- Whether using multiple spectral bands has any benefits compared to a standard EO sensor or EO sensor combined with IR sensor. That includes benefits of having a spectral profile of surrounding background area and objects from the standpoint of more reliable/precise DCT.
- What are the limitations of using MS sensors and computer vision/artificial intelligence (CV/AI) algorithms to process data?
- What computational resources would be required to enable DCT capability on board commercial off-the-shelf sUAS?
- Whether an onboard MS sensor and available feature-finding and matching techniques can contribute to enabling GPS-free navigation for aerial vehicles.

To address these research questions, this study dealt with two applications. One was related to the DCT problem; specifically, it dealt with detecting unexploded ordnance (UXO) with the help of sUAS equipped with a 5-band MS. Thousands of images were obtained using both EO and MS sensors. Artificial
convolutional neural network (CNN) was designed and trained for EO and each spectrum of MS sensors. The second application dealt with visual odometry. A limited set of 2-band MS sensor imagery was used for the analysis. Different feature-finding algorithms were tried.

Findings and Conclusions
The key findings for the MS-based detection of UXO problem are as follows:

- The AI-based UXO detection system seems to be a good representative application where MS sensor could reveal its potential to contribute to the solution of DCT problems.
- As anticipated, the UXO detection capability by individual spectrum detectors is lower compared to that of EO sensor. However, it was found that they are complimentary to each other.
- By applying the two-step integration process, the overall UXO detection capability of MS detector exceeds that of EO sensor by about 13%.
- Using more than one spectral band makes a detection process more reliable. For example, while in some cases Blue and Green detectors were able to detect UXO, other band detectors were not. In some other cases, only the NIR detector was able to detect UXO while all other detectors failed to do so.
- All detectors detecting UXO in their own spectrum band feature a different size of the bounding box and different detection confidence score (i.e., some spectrum detectors detect UXO more precisely than others). For instance, in some cases, the Blue and Green detectors detected UXO more precisely than other detectors. In some other cases, it was the Red and NIR detectors that detected UXO more precisely than the others.

The key findings for the MS-based visual odometry problem are as follows:

- Three feature finding methods (out of eight explored), specifically, ORB, FAST and SURF, seem to provide the best feature finding results for both EO and NIR spectra.
- Features found by EO and NIR sensors, seem to be complementary (not necessarily the same).
- If two consecutive images feature about the same scene, many features can be matched between the images, even though they are far apart (slow flight, high altitude flight, high sampling rate). Even for the specific set of data obtained by a low-flying sUAS when images were taken 10 or even 20 seconds apart, there was a healthy number of the matching features and inliers to produce a compute transformation.

For both applications considered in this study (object detection and vision-aided navigation), the CV/AI algorithms that were developed in the MATLAB development environment worked reliably and did not take more resources than it would be required for processing a standard EO and/or IR sensor output.

Recommendations for Further Research
The overall conclusion from this study is that utilizing small unmanned aerial systems (sUAS) equipped with multispectral sensor (MS) and computer vision/artificial intelligence (CV/AI) algorithms may be very beneficial to Department of Defense and Department of the Navy offering new and enhancing existing capabilities. As such, the recommendation is to continue the assessment of technologies discussed in this study. Further development would involve

- Using a fully equipped sUAS, recording unmanned aerial systems’ sensor position and attitude while taking MS imagery
• Tuning the visual odometry algorithms to match true data provided by the inertial navigation system/global positioning system (INS/GPS)
• Studying effects of operating environment, terrain, altitudes, object size and material, time of the day, weather, number of spectral bands, resolution, narrow field of view.

NPS-21-N107-A: Operationalizing Naval Special Warfare (NSW)/Special Operations Forces (SOF) for the Countering Weapons of Mass Destruction (CWMD) Mission

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Student Participation: LCDR Michael Hicks USN, MAJ Kurt Carlson USA, CPO Michael Walls USN, LT Matthew LeBlanc USN, MAJ Sean Donnelly USA, and MAJ Jake Groves USA

Project Summary
The Naval Postgraduate School (NPS) Counter-Proliferation Studies Program conducted a year-long study on how to posture Naval Special Warfare (NSW) forces over the next five to ten years to support the counter weapons of mass destruction (CWMD) mission. The research team used a qualitative methodology that combined case studies with guided classroom exercises to leverage student operator experience. The study found that special operations forces (SOF) access and placement, influence with foreign partners, and special reconnaissance and direct-action authorities could provide value to the broader CWMD mission. However, additional outreach, training, and education would be required to capitalize on these skillsets. The study also revealed ongoing, underlying challenges. Senior leaders do not currently prioritize CWMD operations and activities, and there is a gap in operational and tactical guidance. This has created confusion over what specific aspects of the CWMD mission maritime special operations forces need to plan for and be prepared to execute. To address these challenges, senior leaders and their staffs need to define and prioritize the mission, establish clear and targeted information and intelligence requirements, and evaluate training and readiness.

Keywords: counter-proliferation, CP, countering weapons of mass destruction, CWMD

Background
This study was designed to inform future NSW planning efforts and force structure decisions, and ensure NSW forces and personnel are postured to achieve the essential CWMD objectives and tasks assigned by United States Special Operations Command (USSOCOM) and geographic combatant commanders employing SOF.

The study explored three basic research questions:
1. What is the unique value proposition of NSW/SOF for the CWMD mission?
2. How can NSW meet current requirements and support the steady-state objectives outlined in the Department of Defense’s (DOD) CWMD Functional Campaign Plan?
3. What metrics should NSW employ to determine if future doctrinal or force structure changes are required?
To address these issues, the research team leveraged an exceptional group of NPS students with diverse backgrounds and operational experience. NPS faculty also conducted an initial baseline and literature review and held a series of classified discussions and meetings with NSW representatives and other key stakeholders, including from the Navy explosive ordnance disposal community, higher echelon units, and the U.S. Special Operations Command. When the COVID-19 pandemic restricted student access to classified materials, the research team worked with the NSW sponsors to develop tailored student research topics in lieu of classified case studies and operational approaches.

Findings and Conclusions
The study identified three overarching findings:

1. **VALUE PROPOSITION: SOF access and placement, influence with foreign partners, and special reconnaissance and direct-action authorities could provide value to the broader CWMD mission. However, additional outreach, training, and education would be required to capitalize on these skillsets.** Our research identified several areas where NSW forces could provide value to the DOD’s broader CWMD mission, particularly given NSW’s access and placement and influence with foreign partners. In fact, four of the five student research areas recommended utilizing NSW’s influence with foreign partners to build partner capacity. However, in all cases it will require NSW forces to better integrate with other departments and agencies already working in targeted areas, and ensure that platoons are properly trained and educated, particularly before engaging foreign partners or taking on building partner capacity efforts. There are discrete communities within the department and across the interagency that focus on specific aspects of the CWMD mission. For NSW forces to add value to the broader CWMD mission, its leaders and staff will need to work within these distinct communities to understand what activities are already occurring and gain consensus on where specifically their access, authorities, and capabilities can fill gaps.

2. **GUIDANCE AND REQUIREMENTS: There is no clear operational or tactical guidance that defines what specific aspects of the CWMD mission maritime special operations forces need to plan for and be prepared to execute.** The study found that there is no shared understanding of what constitutes the “CWMD mission,” let alone who does what to support it. Some aspects of the community view “CWMD” as synonymous with WMD crisis response or device defeat operations, while others focus on upstream pathway defeat activities, or the ability to conduct operations in an environment where chemical, biological, or nuclear weapons have been used. The department’s broad, higher-level guidance has not been sufficiently translated into clear operational or tactical guidance for NSW commanders and their staffs. This gap in guidance creates confusion and will make it difficult for the command to assess future manpower, training, and capability requirements to support CWMD objectives. It will also make it challenging to develop specific metrics for tracking progress and determining whether future adjustments are needed.

3. **PRIORITIZATION: CWMD operations, activities and investments are not currently a priority.** One of the core challenges encountered throughout this study is that CWMD activities are simply not a priority for most commands. While the USSOCOM commander occasionally emphasizes the mission given his role as the DOD coordinating authority for CWMD, this rarely translates into action at the tactical or operational levels. Furthermore, the geographic combatant commanders
largely ignore this mission space, assuming in part that national level assets will handle any scenario that arises given the longstanding crisis response capabilities that elite elements bring to bear. There are exceptions to this, to be sure, but the overall lack of demand signal from senior leaders has had a cascading affect across Naval Special Warfare Command and its subordinate commands.

Recommendations for Further Research
Future work on how to posture Naval Special Warfare (NSW) forces to support the counter weapons of mass destruction (CWMD) mission should consider three recommendations.

1. Define and prioritize the mission(s). As this study found, the lack of clarity surrounding which elements of the CWMD mission NSW forces should support causes confusion and makes it difficult for lower echelon elements to consistently interface and train with the necessary partners and enablers. This could largely be overcome if combatant commanders articulate clear priorities and actively push elements to train for and exercise certain types of operations. In addition, Naval Special Warfare Command (NSWC) should:

   a. Engage specific CWMD communities. NSWC and its subordinate commands should work with the Navy explosive ordnance disposal community, geographic combatant command and theater special operations command representatives, and Defense Threat Reduction Agency-forward deployed support elements to continue to explore and define tasks and responsibilities for different scenarios in the early phase of a crisis. As progress is made in this area, it will set the stage for follow-on engagements with other communities to better understand how NSW’s access and authorities might be leveraged for other non-crisis CWMD operations.

   b. Influence higher level guidance and refine NSW tactical guidance. Guiding documents at the tactical level are derived from guidance at each higher echelon. Ensuring that higher level guidance prioritizes the mission space and highlights specific CWMD objectives and tasks will help clarify which elements of the CWMD mission NSW forces should be prepared to support. This can be done, for instance, in theater special operations command mission statements, Command Vision statements, and as call-outs in relevant lines of effort in command Areas of Focus.

2. Establish clear and targeted information and intelligence requirements. NSWC should work with United States Special Operations Command (USSOCOM) to sensitize the force to WMD threats, pathways, and CWMD authorities. To do so, USSOCOM should refine its information and intelligence requirements and disseminate them among operational units. Once SOF personnel are sensitized to these requirements, they will also be better positioned to utilize existing mechanisms to feed into the broader intelligence architecture.

   a. Add pre-deployment threat briefs. Educating forces slated for deployment on specific threats and CWMD tasks could create additional opportunities and set the stage for future building partner capacity efforts. This would ensure that training plans for partners in regions with significant illicit trafficking, for instance, support wider CWMD efforts.
3. **Evaluate training and readiness.** Going forward, the command should carefully review the training pipeline to ensure its forces and supporting elements understand both the broader strategic picture and the tactical mission(s) they are being asked to undertake. A review of CBRN defense-related training is also urgently needed. As SOF continue to transition from counterterrorism-focused operations to actions that support strategic competition, there is an increased risk of having to sustain operations in a contaminated environment. As such, NSWC should review the CBRN defense elements already incorporated in its training pipeline to ensure it is suited to the current and future threat environment.

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**NPS-21-N109-A: In-Depth Analysis of Evaluation Practices and Criteria for Competency-Based Aviation Training Models**

**Researchers:** Mr. Joseph Sweeney and CDR Kathleen Giles USN

**Student Participation:** No students participated in this research project.

**Project Summary**
This literature review was conducted to find and analyze practices and criteria that can be used to both accelerate the training process for new pilot students in the Navy aviation training pipeline and potentially improve pilot proficiencies throughout their flying careers. Conducting the initial search for articles on competency-based training (CBT) in a pilot training program using Google Scholar, the Defense Technical Information Center, and the Naval Postgraduate School’s Calhoun search engines narrows the list of potentially useful sources from several million to several hundred. CBT has been shown to produce significant improvements in developing training syllabi as well as evaluating progress and effectiveness in many professional fields. Studies have examined the ability of a student to progress rapidly through initial training phases based on demonstrated abilities to perform specific tasks that have been developed prior to the formal training process. Measuring a pilot’s experience based only on flight hours flown does not provide a complete evaluation of skill level achievement. CBT processes can provide a more detailed assessment of pilot performance. Follow-on work should examine the details of specific tasks that are likely to be validated in the early training process (i.e., airmanship and basic communications) to allow the student pilot to more quickly progress to the more demanding evolutions such as formation flights and carrier landings.

**Keywords:** pilot training, competence, competency, competency-based training, CBT, competency-based education, CBE, evidence-based training, EBT, performance-based training, PBT, training

**Background**
The current student pilot training pipeline is severely backlogged. As a result, the Navy assigns newly commissioned officers to temporary billets before beginning pilot training. This study was conducted to determine how the training process can be shortened by reducing the time to learn airmanship skills. A literature review was conducted to examine CBT success as well as locate programs that may be used as models for the Navy process. CBT could be used to reduce the amount of time required to move a student pilot through some of the initial training requirements.
The International Civil Aviation Organization (ICAO) developed an outline in their Doc 9995, “Manual of Evidence-based Training.” This document is designed “to develop and evaluate the identified competencies required to operate safely, effectively and efficiently in a commercial air transport environment whilst addressing the most relevant threats according to evidence collected in accidents, incidents, flight operations and training” (ICAO, 2013).

ICAO (2013) defines competency as “a combination of skills, knowledge, and attitudes required to perform a task to the prescribed standard” (Annex 1). The Department of Defense (2016) describes competency as “an observable measurable pattern of knowledge, abilities, skills, and other characteristics that individuals need to successfully perform their work” (p. 21).

A criticism of CBT programs is they only produce a minimum level of performance since the assessments tend to evaluate “met or did not meet” requirements. In some cases, the standards are not clearly delineated, obscuring the assessment process. This is being overcome in programs similar to Mendonca et al.’s (2019) study at Purdue, where three learning levels have been defined—emerging, developing, or proficient—to differentiate between performance levels. If the “meets requirement” evaluation is considered insufficient to allow the student to progress to the next level, then that requirement needs to be re-evaluated. As they say, if the minimum’s not good enough, then it must be raised.

Researchers in Norway and the Netherlands investigated the feasibility of competency-oriented, performance-based training for Air Force combat pilots to maintain skill proficiency. They used a phased approach integrating several training theories starting with CBT, adding performance-based training (PBT), and then supplementing it with evidence-based refinements. They found their approach was well-suited for simulation-based training because scenarios were easier to control than live training. This method is an alternative to the commonly used frequency-based refresher training approach that takes place on a predetermined schedule. Fjærbu et al. used PBT to focus on desired proficiencies and used actual pilot performance to determine the training amount and timing. To support this training model, pilot performance needs to be measured as objectively as possible and instructor evaluations need to be discriminative and standardized, not just pass or fail.

Holt and Perry (2011) developed the Universal Competency Assessment Model (UCAM) to provide a structured methodology yielding a repeatable, transferable, measurable, based on best practices, and tailorable. This provides the skeleton for the Navy aviation pilot training program to design the assessment process.

**Findings and Conclusions**

This literature review was conducted to find evidence of successful use of CBT in aviation training programs which, when incorporated into the current pilot training program may allow for a reduction in the overall training program and generate more highly-skilled pilots when they report to the Fleet Replacement Squadrons to join the front line of skilled, capable pilots in the fleet.

Franks et al. (2014) state “In aviation, there is debate emerging around the idea that something more than learning and performance of discrete tasks is essential for developing higher order problem solving skills and their application for performing complex tasks of the kind that are routinely encountered by pilots during flight. This indicates that some instructional practitioners see the need for CBT to be used in a
more holistic and integrated way than is the current practice in pilot training” (p. 143). This aligns with the challenge of measuring a student pilot’s achievement of specific tasks in assessing whether they are qualified to progress to the next step in the training program. Most CBT programs reviewed applied a binary evaluation to the student’s achievement—either they met the requirement, or they did not.

There are problems with the binary evaluation process (Pass/No Pass) used in many CBT processes. Providing a binary CBT process for the earlier, less complex tasks in the pilot training pipeline can allow quicker progress through those earlier stages, shortening the time required to complete initial pilot training. For more complex task evaluations, the issue of a binary evaluation can be overcome as shown in Mendonca et al.’s (2019) study by providing more details in the evaluations. Utilizing CBT processes for more experienced pilots can also realize improved effectiveness in the training and assessment process but will require a more involved development process and more training for those instructors providing the training and performing the assessments.

Assembling a CBT process will require substantial investment of time and energy since it must be tailored to the individual and provide meaningful assessments throughout the process. Providing a fixed training program that everyone must proceed through is simpler to utilize and walk everyone through but lacks the flexibility to move students through the tasks they have already mastered in a more effective and efficient manner.

Many articles discuss the shortcoming of the CBT process, where the more advanced skill sets such as critical thinking, decision-making, problem-solving and team interactions are lacking or not addressed. Any Navy-oriented CBT process should include these skills since the pilots will be expected to be able to think critically, make decisions, solve problems, and will nearly always be working as part of a team focused on carrying out a mission.

To enhance the Navy’s student pilot training program, it is recommended that a detailed CBT program be developed, using a structured approach similar to the UCAM developed by Holt and Perry. ICAO Doc 9995 could be used as a starting point to develop similar specific tasks to train Navy pilots.

**Recommendations for Further Research**

Implementation of a competency-based training (CBT) system in the Navy’s pilot training program would include an analysis of current flight training evolutions with consideration for which requirements may be met by other achievements.

Future research should focus on developing and analyzing use cases to support the training process of upcoming pilots. This would include comparing the fleet performance of pilots being trained via the legacy process to those new pilots being trained with a CBT approach.

Additionally, research should investigate methods for accomplishing training objectives with simulator use to reduce impact on aircraft and instructor pilot availability.
References


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**NPS-21-N114-A: Modeling SIGINT**

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**Student Participation:** LT Christina Reeder USN

**Project Summary**

The Navy is considering installing signals intelligence (SIGINT) equipment onto manned and unmanned maritime patrol aircraft to add another source of detection capabilities for anti-submarine warfare (ASW). However, the influence of SIGINT on mission effectiveness is unclear since existing simulations do not explicitly quantify SIGINT sensor impact. To address this deficiency, this study investigated a modeling approach for quantifying the operational effectiveness of SIGINT. The project team investigated existing SIGINT modeling methods, focusing on two simulation tools in use by the sponsor organization: the Naval Simulation System (NSS) and the Advanced Framework for Simulation, Integration, and Modeling (AFSIM). The project team formulated a mathematical model of probability of signal detection using parameters describing transmitter and receiver performance characteristics together with antenna patterns and characteristics of the dynamic scenario environment. The team used the MATLAB mathematical modeling tool to compute look-up tables for the probability of detection for integration into the simulation tools. The team proposed an operational scenario for implementation in a simulation to evaluate the contribution of SIGINT information to warfighting effectiveness.

The physics-based transmitter-receiver model enabled representation of a range of systems through performance parameters. Modelers in the sponsor organization can represent specific systems through substitution of performance values for those systems into the equation.
The project team recommends that Naval Air Systems Command (NAVAIR) modelers use the MATLAB implementation of the transmitter-receiver equations to generate a probability of detection look-up table for integration in AFSIM. Recommendations for future study include: (1) examining how a platform using SIGINT can collaborate with a similarly enabled SIGINT-capable platform; (2) examining how that platform can collaborate with other SIGINT sensors (e.g., ground-based or space-based); and (3) further investigating fusion modeling capabilities in AFSIM to enhance its application to these studies.

Keywords: signals intelligence; SIGINT; electronic intelligence; ELINT; communications intelligence; COMINT; modeling and simulation; Navy Analytic Agenda; fusion; Naval Simulation System; NSS; Advanced Framework for Simulation, Integration, and Modeling; AFSIM; MATLAB

Background
The Naval Air Systems Command (NAVAIR) Mission Engineering and Analysis Department (MEAD) conducts an annual cycle of engineering and mission-level modeling to support investment decisions for the Office of the Chief of Naval Operations Director of Air Warfare (OPNAV N98). The Navy is considering installing signals intelligence (SIGINT) equipment onto the P-8A Poseidon maritime patrol aircraft and MQ-4C Triton unmanned surveillance aircraft to generate an additional source of detection capabilities in support of anti-submarine warfare (ASW). However, SIGINT influences on mission effectiveness are unclear since existing simulations do not explicitly quantify SIGINT sensor impact. This study investigated a modeling, simulation, and analysis approach for quantifying the operational effectiveness of such systems.

The study team focused on two principal considerations. The first was to formulate the complex transmitter-receiver equations associated with SIGINT sensor performance. Modeling SIGINT sensing involves well-established but complex physics-based mathematics. Real-world input factors are highly classified and hard to obtain. The researchers decided to take a general approach by parameterizing the transmitter-to-receiver equations across many relevant factors, leaving the actual determination of specific factor values to the NAVAIR modelers. The Office of Naval Intelligence (ONI) has the specific threat emitter factors, and the SIGINT sensor program office possesses the factor specifications related to the sensing receivers. On the transmit side, this includes such factors as power, gain, frequency, wavelength, waveform, range, and duration. On the sensor side, factors include sensitivity, filtering, frequency, dynamic range, directionality, and number of receivers. Antenna gain on both sides depends on antenna patterns and the transmitter-receiver geometry, which is generally highly dynamic and scenario/operations-dependent.

The second principal consideration was conversion of the SIGINT sensor performance into mission-level tactics, followed by determining which of the sponsor’s available simulation tools, AFSIM or NSS, was suitable for this investigation. NSS possesses data processing architecture options that allow information from multiple sensors to be “fused” in a platform. AFSIM possesses a modern simulation software architecture, providing users greater flexibility in model development. Moreover, its sizable and growing user community offers opportunity for model sharing, reuse, and adaptation. Because of its flexibility and long-term improvement potential, the study team chose AFSIM as the preferred simulation for this study.
The study team, including NPS student involvement, implemented the transmitter-receiver equations in the MATLAB mathematical modeling tool for computing output values across the range of input parameters. The researchers found that computed results can be integrated with AFSIM through look-up tables, the computations can be called through software linkage to MATLAB, or the computations can be implemented directly in AFSIM scripts.

The study team also outlined an operational scenario to represent a tactical situation within which the effects of availability of SIGINT data can be evaluated. However, the sponsor’s modeling team already had an operational scenario they were using, so they were most interested in the transmitter-receiver signal equations.

Findings and Conclusions

The study team determined that SIGINT modeling requires attention to detail but is executable using a combination of MATLAB for executing the complex transmitter-receiver equations and AFSIM for representing and executing the mission-level scenario dynamics. The team was able to use MATLAB to generate a table of results across a large number of relevant input parameters. This makes the resultant MATLAB code and the table unclassified, since the equations and results do not involve information about specific real-world sensors or transmitters. MATLAB can be linked to the AFSIM software or the equation can be implemented in AFSIM scripts so that AFSIM can execute the equations each time a SIGINT sensor could possibly detect a signal. If there were thousands of computations per run—for instance in a mission assessment where the targets of interest included surface ships as well—then pre-computing the data and using look-up tables may be more efficient. For real-world considerations, modelers need to consult experts to obtain specific values for input parameters related to target-of-interest transmissions and own-force sensor performance.

Investigation of the sponsor’s prominent simulation tools, NSS and AFSIM, showed that the transmitter-receiver computations can be implemented through look-up tables or through direct integration of the mathematical formulation. The most direct way to integrate the computations in NSS is through look-up tables; however, the NSS developer would need to be contracted to do the work. Compared to NSS, AFSIM provides a more flexible software architecture for embedding this computation while also supporting a growing community of modelers in the Navy.

In conclusion, researchers determined that SIGINT modeling is achievable using a combination of MATLAB for executing complex transmitter-receiver equations and AFSIM for modeling the mission dynamics. The sponsor’s modelers found great value in the ability to compute probability of detection using the mathematical formulation.

For applying the study results, the study team recommends that the NAVAIR modelers use the MATLAB code to generate a multi-dimensional look-up table so that when their mission model calls for a possible SIGINT detection, the collected factors can be used to determine the probability of detection. From there, the rest of the modeling is a matter of executing preset tactics tables, something these modelers are already proficient in doing.

The study team also recommends that the modelers use AFSIM for their mission modeling, for several reasons. First, in AFSIM it is easy to create a call to a look-up table.
Second, if it became necessary, AFSIM can link to the MATLAB software to initiate execution of the computations, or the computations can be implemented directly in AFSIM scripts. These AFSIM model adjustments do not require contractor work nor any special license accesses. Furthermore, AFSIM has a robust user group where help is readily available from other developers/users.

**Recommendations for Further Research**

One of the factors in the transmitter-receiver signal detection equations deals with how the receiver captures the signal. Researchers calculated three options: (1) a very conservative assumption, called the non-coherent conservative assumption; (2) a second less conservative assumption called the non-coherent envelope; and (3) a third, more optimistic assumption, called the coherent signal. Given the same distance between the transmitter and the receiver, look-up tables showed a significant difference in probability of detection based on which of these factors is selected. The study team recommends discussing this critical factor with the Office of Naval Intelligence (ONI, for information on threat systems) and the signals intelligence (SIGINT) sensor program office to ensure the correct selection is made for calculating the probability of detection.

While the Advanced Framework for Simulation, Integration, and Modeling (AFSIM) is the recommended mission modeling approach, there are cases where the Naval Simulation System (NSS) might be appropriate. If understanding SIGINT signal fusion across similar and dissimilar platforms and sensors is important in future modeling, then NSS may be a more appropriate tool, since NSS has specific modeling capabilities for fusion techniques. Alternatively, AFSIM could be used, but fusion algorithms may need to be added to the AFSIM mission model, which would require fusion algorithm expertise. The literature review indicates that Naval Air Systems Command (NAVAIR) possesses such expertise. Moreover, the user base for AFSIM is rapidly growing, creating a large community of developers who may already be pursuing these kinds of improvements in AFSIM modeling capabilities.

Additional recommendations for future study include: (1) examining how a platform using SIGINT can collaborate with a similarly enabled SIGINT-capable platform; (2) examining how that platform can collaborate with other SIGINT sensors (e.g., ground-based or space-based); and (3) further investigating fusion modeling capabilities in AFSIM to enhance its application to these studies.

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**NPS-21-N210-B: Unmanned Carrier Concept in Support of DMO**

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**Student Participation:** Mr. Winston Arnold CIV, Mr. Craig Fletcher CIV, Mr. Richard McCann CIV, Mr. Jeffrey Patel CIV, and Mr. Jairus Potts CIV

**Project Summary**

This project assesses operational and design considerations for utilization of an unmanned vehicle carrier (UVC) concept in support of distributed maritime operations (DMO). That assessment informs investment and development of operational concepts related to the utilization of unmanned systems, a potential UVC, and their integration with the manned fleet.
This project develops architectural representations of DMO, to include a definition of associated systems as well as related operational activities. Those representations serve as the baseline for simulation model development that examines the impact that the UVC may have on operational availability and sustainment. Analysis of the simulation was conducted in two phases. The first phase assessed the overall impact of the UVC in a representative 90-day operational scenario. That analysis indicated that the UVC has a positive impact on operational availability. Notably, the impact is magnified for unmanned systems with limited organic endurance. Employment of the UVC resulted in an improvement of as low as 6% and as high as 31% on operational availability for different classes of unmanned systems. The second phase of analysis examined the design characteristics of the UVC to identify key performance drivers for the UVC. That analysis found that the number of well decks for launch and recovery of unmanned surface vessels and unmanned undersea vessels had a larger impact than the number of launch and recovery stations for unmanned aerial vehicles. Similar to assessment of the fixed UVC configuration, the analysis showed that the impact of increases to the number of recovery and maintenance stations was more substantial for unmanned systems with limited endurance, suggesting that appropriate design of the UVC itself is inherently coupled with the design characteristics of the systems the UVC supports.

**Keywords:** distributed maritime operations, DMO, unmanned systems, model-based systems engineering, discrete event simulation

**Background**

As the U.S. Navy develops systems and operational concepts with an emphasis on a Great Power Competition, there is an increased emphasis on the ability to mass effects while remaining geographically distributed. The US Navy is increasingly prioritizing the ability to project offensive capability (Gilday, 2021). A recent push towards the definition of the distributed maritime operations (DMO) concept (Jensen, 2015) and distributed operations (Rowden, Gumataotao, & Fanta, 2015) has emphasized that the future force may be organized in non-traditional ways to realize fighting power. This DMO concept will allow the Navy a greater diversity of options to conduct operations through coordinated use of sensors, platforms, and weapons. This is facilitated through the merging of resources, information, and technologies across the fleet. In support of those larger objectives, unmanned systems have the potential to act as a force multiplier that increase lethality while reducing the risk to manned systems.

Unmanned systems have the potential to augment the capabilities of the existing fleet in future DMO focused structures. Notably, Gilday (2021) emphasizes that the future fleet will be a larger, hybrid design that relies on integrated manned and unmanned systems to enable sea control and sea denial. Recent literature, such as Joyce (2018), suggests that in-development unmanned systems are realistic force multipliers in the near term. To support that vision, this research investigated the utility, viability, and critical capabilities for an unmanned vehicle carrier (UVC). The focus of this project is the potential for the UVC to raise operational availability, limit re-arm/re-supply down time, and allow for forward at sea maintenance of unmanned systems. This research develops candidate operational concepts for the UVC in support of DMO. Those operational concepts are detailed in architectural representations of both the system and operational level considerations that influence the design and conceptualization of the UVC. Those alternative system concepts are analyzed using an operational simulation model developed in the discrete-event simulation software ExtendSim.
The simulation effort, summarized in Arnold et al. (2021), positions the UVC in a representative operational scenario and describes the system and operational considerations using a series of Department of Defense Architectural Framework (DoDAF) products. Those DoDAF products are used to define a baseline set of behaviors for all associated systems, specifically the unmanned aerial vehicles (UAVs), unmanned surface vessels (USVs), and unmanned underwater vehicles (UUVs) that could be supported by the UVC. The activities and systems described in those products are implemented in an ExtendSim model that captures both the operational availability and persistent dwell time for the UAVs, USVs, and UUVs supported by the UVC. A baseline UVC configuration is simulated to compare the isolated impact on operational availability and dwell time that the UVC has versus force structures that do not employ a UVC. Subsequently, the simulation model systematically varies both the characteristics of each UAV, USV, and UUV as well as the characteristics of the UVC, and regression analysis is conducted to highlight the characteristics that have the largest impact on operational performance.

Findings and Conclusions
This project utilized the output of a discrete event simulation model built in ExtendSim to determine the operational and design characteristic of the UVC that improved operational availability and dwell time for associated unmanned systems. In the first phase of analysis, a baseline UVC was simulated and compared to force structures that did not employ a UVC. The baseline UVC design assumed a system with eight UAV maintenance bays, four UAV refueling bays, eight multi-purpose well deck bays, four multi-purpose ship side bays, and eight well deck maintenance bays. The model assumed that the UVC was capable of support for two classes of UAV (the MQ-8 Fire Scout and the RQ-21 Scan Eagle), two classes of USVs (a large USV [LUSV] and medium USV), two classes of UUVs (a large displacement UUV and an extra-large UUV), as well as fast inshore attack crafts and fixed characteristics associated with each supported system, specifically the number of each system, the number of crew members dedicated to each system, launch capacity, recovery capacity, and system endurance. When compared to the results for force configurations that did not employ a UVC, there was a statistically significant impact on operational availability for every support system except the LUSV. The increase in operational availability ranged from 6% for the medium USV (operational availability increased from 81% to 87%) to 31% for the extra-large UUV (operational availability increased from 60% to 91%). Generally, the impact was more substantial for systems with lower endurance. This was particularly evident when the LUSV was considered. Because the endurance was almost equivalent to the 90-day timeframe simulated in the model, there was no statistically significant impact on operational availability for the LUSV resulting from employment of a UVC.

After quantifying the general impact of UVC employment on operational availability, a more detailed analysis was conducted to determine the design and operational characteristics that had the largest impact on performance. Each of the fixed characteristics in the baseline configuration was systematically varied in subsequent simulations. A total of 21 design characteristics were varied in the model, and a 320-design point nearly orthogonal Latin hypercube design was generated in the statistical software JMP Pro 15 to define the design points. Each design point was replicated 30 times to account for stochastic variability in the model. Generally, analysis indicated that the number of UAV launch and recovery bays, originally fixed at eight and varied in the model, had limited impact for each class of unmanned systems. This indicates that eight UAV launch and recovery bays likely represents an adequate upper bound. The number of well deck bays and maintenance bays (used for both USVs and UUVs) had a larger impact in the model.
Analysis demonstrated that operational availability increased and that at least three side bays and five maintenance bays likely represent a lower bound on preferred UVC design.

**Recommendations for Further Research**

This project developed a discrete event simulation of the role that an unmanned vehicle carrier (UVC) may play in distributed maritime operations using ExtendSim. Future work is recommended to add detail to the model to represent additional system characteristics and operational scenarios. Specifically, using the recommended system configurations from this project, additional modeling could be done to explore the impact of a reduction to the number of unmanned aerial vehicle (UAV) launch and recovery bays and a corresponding increase to the number of unmanned surface vessel (USV)/ unmanned underwater vessel (UUV) well deck bays and maintenance bays. That work should consider the number of UAV launch and recovery bays modeled in this study as an upper bound and the number of USV/UUV well decks and maintenance bays as a lower bound. Additional modeling efforts may also benefit from additional fidelity in terms of maintenance intervals and individual system endurance. Analysis in this project suggested that individual system endurance had a statistically significant impact on performance; accordingly, the introduction of additional failures for each class of unmanned system may further stress the system in informative ways. Similarly, expansion of the model to include additional operational scenarios would improve the applicability of the recommendations from this project. Specifically, introduction of combat losses, changes to mission tasking (and the associated launch and recovery schedule for each class of unmanned system), and overall operational duration would be worthwhile additions to the simulation model that would further inform UVC design and employment.

**References**


**Project Summary**

The U.S. Navy is expanding its force of unmanned surface vessels, including medium displacement unmanned surface vessels (MDUSV). The integration of MDUSVs into Carrier and Expeditionary Strike Groups (C/ESGs) needs to be considered. Survival of C/ESGs depends upon many factors, including robust defenses against submarine-launched torpedoes and anti-ship missiles that can be deployed from numerous platforms. Some existing C/ESG anti-submarine and anti-missile defenses require deploying technologies that can be used by these threats to target the C/ESG. One potential approach to establishing reliable defenses is the deployment of unmanned surface vessels in these defense roles. With this approach, defensive technologies may be distanced from the C/ESG and deployed on platforms that present lower risk to the C/ESG and its personnel.

This research effort was divided into two parts, the first being an examination of MDUSV integration into C/ESGs through wargaming via the Joint Campaign Analysis operations research class at the Naval Postgraduate School. The second was through a class modeling effort.

Our findings included (part one): Utilizing MDUSVs as a force multiplier can greatly reduce the potential losses of blue force combatants while also increase the survivability of the C/ESGs. Defensive platforms (MDUSVs) put at a distance from the C/ESG reduce the risk to personnel of these groups. Part two findings: Recommendations are to add swarm capabilities to MDUSVs, automate a handoff capability for control of MDUSVs, provide more holistic Command and Control (C2) support, implement operator hierarchy, and use LOS relays among aircraft and ships to extend LOS RF bands and using multi-hop Satellite Communications (SATCOM).

**Keywords:** models, MDUSV, CSG, ESG, strike group protection, CONOPS, optimization, C2, communications, wargaming, joint campaign analysis

**Background**

This project studied and modeled integration of Medium Displacement Unmanned Surface Vessel (MDUSV) capabilities into a C/ESG to test new tactics and procedures. The addition of MDUSVs to a Strike Group is an exciting concept developed to meet the requirements of evolving best practices, as missions and best practices are identified. In part one of this effort NPS students analyzed MDUSV operations as part of a C/ESG in a Joint Campaign Analysis class. In the future, naval exercises offer an excellent opportunity to take these suggested tactics, techniques, and procedures and integrate them with Fleet Operations during both the planning and execution stages. The results produced from this study may establish a basis for CONOPS improvements for MDUSV usage.
In part two, Naval Postgraduate School (NPS) students modeled the integration of MDUSVs into C/ESGs in computer science classes.

Fleet commanders could benefit from this study using recommendations for MDUSV integration into the fleet. Through our research we applied both wargaming and modeling methodologies to answer the question of integration.

Our methodologies included for (Part One) a southwest Pacific Ocean scenario pitting blue C/ESG type defensive forces (combatants and MDUSVs) against a red two-wave attack (frigates and destroyers). The research included four scenarios to analyze red surge tactics against various numbers of blue forces (corvettes, Expeditionary Advanced Base Forces (EABF)-Littoral Combat Ships (LCSs), and MDUSVs). An analysis was conducted running simulations as to the expected percentage of blue and red victories and the survivability of each class of blue vessel during the two-wave red attack.

In Part Two. An NPS Computer Science class was divided into two groups to conduct a modeling study on MDUSV integration. The teams would create a brief statement of purpose for the proposed system model, list system stakeholders with a sentence describing the role of each one, develop a high-level context diagram showing the interactions between the proposed software and the external systems with which it communicates, and provide a final report on the results.

Findings and Conclusions
Our findings included (Part One): Utilizing USVs as a force multiplier can greatly reduce the potential losses of blue force combatants while also increase the survivability of the C/ESGs. Defensive platforms (MDUSVs) put at a distance from the C/ESG reduce the risk to personnel of these groups. Part Two findings: Recommendations include adding swarm capabilities to MDUSVs, automating a handoff capability for control of MDUSVs, providing more holistic C2 support, implementing operator hierarchy, using line-of-sight (LOS) relays among a/c and ships to extend LOS radio frequency (RF) bands, and using multi-hop SATCOM.

In order for MDUSVs to be integrated into the fleet, all aspects of their potential uses, and consequences of their participation, must be examined. The topic sponsor will use the input received from this research to further the efforts of the MDUSV CONOPS group and integration of MDUSVs into the fleet. It is recommended that further studies be conducted on integrating MDUSVs into various roles in C/ESGs to include findings from both parts of this research effort. Studies involving C/ESG defense, Anti-Submarine Warfare (ASW)/Anti-Ship Cruise Missile (ASCM) defense, and communications/C2 implications should be considered.

Recommendations for Further Research
Future research could examine various red tactics and force levels in additional to more precise Command and Control (C2) in US vessels such as using Medium Displacement Unmanned Surface Vessels (MDUSVs) to mimic swarming tactics against red combatants.

Another specific challenge for MDUSVs is the calculation of on-station time (OST). Many variables affect OST and should be considered in algorithms that support OST predictions. One recommendation is to predict a “baseline” on-station time by establishing “standard conditions.”
Variables such as those listed above can be applied to the standard conditions algorithm to calculate variances needed to predict OST.

Ballistic Research Laboratory (BRL), now Army Research Laboratory (ARL), used a similar approach when developing firing solutions for artillery weapons. Standard conditions included weapon height at sea level; ambient temperature; wind speed; wind direction; air humidity; air density; obstacles (hills, trees, etc.); weapon type; barrel wear; propellant type/lot/age; projectile type and weight, and many other variables. Furthermore, the firing solutions considered weather conditions at various altitudes through which the projectile would travel on its path to the target. For this, meteorological instruments were flown aloft to capture weather data at prescribed altitudes up to maximum ordinate (apex) of the projectile. Current technologies, including lasers, may suffice for collection of weather information. Eventually, battlefield computers actually “flew the projectile” via simulation.

Computer simulation of MDUSV OST may be a viable approach to predicting OST. The teams recommend further exploring standard conditions for this problem and determining whether it is practical to observe the relevant variables during missions, and whether onboard computers can carry out the analogous simulations to provide useful predictions of MDUSV OST.

NPS-21-N359-A: Mine Warfare in Great Power Competition

Researchers: LCDR Ross Eldred USN Ret.
Student Participation: Maj Matthew Simard USMC

Project Summary
Recent advancements in offensive mine warfare demonstrate the sophistication of the latest mine technology and growth in general interest in mine warfare. A systems-thinking approach is used to identify opportunities for further advancement in mine warfare within the context of great power competition, specifically, the deterrence of forceful reunification of Taiwan to mainland China. The link between the geographical nature of the minefield and the importance of psychology in the implementation of effective naval mining is then pursued through a brief review of the ancient Chinese concept of Shi, which relates intimately the natural (physical) and psychological aspects of the battlefield. Problem space definition follows the application of Shi philosophy to Chinese grand strategy and key physical and psychological factors are identified, along with corresponding opportunities for exploitation. The identification of capability gaps enhances the creative synthesis of new ideas, including both novel technology concepts and new applications of existing technology in an effort that considers the “mine” foremost as an “effects-delivery mechanism.” Finally, the strategic philosophy and context characterized at the beginning of the study is combined with the alternative technologies identified thereafter and operational art is applied to generate a concept of operations (CONOPS) entitled The Kelp Road Initiative (KRI). The author recommends the further research and development of effects-based delivery vehicles and payloads incorporating the technologies explored.
Keywords: offensive mine warfare, great power competition, electromagnetic pulse, EMP, Wreck Interior Exploration Vehicle, WIEVLE, lighter-than-air gas delivery system, LTA, Resetting Anchor Antenna Tether Mechanism, RAATM, Shi, Chinese Communist Party, CCP, Kelp Road Initiative, KRI

Background
The chief goal of the study, as directed by the Mine Warfare Office (N952), was to identify and examine new ways of thinking about offensive mine warfare, driven by effects, and beyond the conventional use of the mine as a kinetic anti-ship or anti-submarine weapon system. The results of the study may be of benefit to this office (N952) as well as any offices, directorates or departments within the Department of Defense concerned with unmanned systems operations, mine warfare, and operational planning (especially in the context of China and Taiwan).

The study begins with the selection of a key aspect of the Great Power Competition strategic context: the forceful reunification of Taiwan with mainland China. The link between the geographical nature of the minefield and the importance of psychology in the implementation of effective naval mining is then pursued by a brief review of the ancient Chinese concept of Shi, which relates intimately the natural (physical) and psychological aspects of the battlefield and is, therefore, most handily applicable to mine warfare and the current stage of competition: the Grey Zone spectrum between peace and war (Jullien, 1995). This philosophical foundation is then applied to key aspects of Chinese grand strategy, its implications in the reunification of Taiwan through force, and the deterrence thereof. The problem space is then defined, through which key physical and psychological factors are distilled, and corresponding opportunities for exploitation are identified. The literature review continues with a brief examination of the evolution of mine technology, beginning from the early history (with an emphasis on psychological factors) through modern technology (with an emphasis on system architecture) and concludes with the identification of common threads in mine system design.

The identification of capability gaps completes the foundation for the creative synthesis of ideas leading to new technological alternatives to help answer the question of what a mine could be while exploiting the opportunities identified in the problem space exploration. The research examines applications for both existing and novel technology toward undersea infrastructure, payloads, and delivery vehicles, emphasizing variety of effects to maximize utility at various levels of conflict. One such technology examined is the Wreck Interior Exploration Vehicle (WIEVLE), an experimental unmanned underwater vehicle platform under development by the author at the Naval Postgraduate School, which may directly benefit future mine warfare development by carrying unique payloads and enabling operations in confined spaces or entanglement-prone areas such as the littorals. The author has recently submitted this vehicle and other related mechanisms for patent and published the work in a marine science journal. (Hevey et al., 2021; Eldred et al., 2021) The study concludes by combining the strategic philosophy and context explored early in the effort with the alternative technologies developed later. Finally, operational art is applied to this combination to generate the KRI CONOPS.

Findings and Conclusions
The conclusions of this study consist of the identification of eight factors, psychological and physical, that bound the problem space within the strategic context; ten corresponding opportunities for exploitation; three common threads in the evolution of offensive mine systems; four corresponding capability gaps; and
system design alternatives within the categories of undersea network infrastructure, novel payloads and novel delivery vehicles (including WIEVLE). The eight factors bounding the problem space include the psychological factors of time, fear, and objective, and the physical factors of shores/littorals, sea, seabed, air, and space. The three common threads in offensive mine technology include (1) the principal goal of sinking enemy vessels (submarine and surface) via warhead delivery, (2) the generally large, heavy size characteristics of mines, and (3) the fact that operations remain within with the water column. Corresponding capability gaps include (1) the lack of a systematic, technological effort to leverage Shi, (2) the lack of scalability of response and corresponding options for Grey Zone conflict, (3) the lack of small-profile, expendable platforms (effects-delivery vehicles) and (4) capability of operations outside the physical boundaries of the water column. Specific technologies are discussed in detail as alternatives in answer to these capability gaps.

The final artifact of the study is the generation of a CONOPS entitled The Kelp Road Initiative (KRI), which was briefed by the author at the Naval Postgraduate School 2021 Warfare Innovation Continuum workshop. The KRI CONOPS provides the creative background for the implementation of the various findings of the primary effort. The author’s fervent hope is that this study will illuminate one possible path for the mine warfare community, the Navy and the nation to approach the art and philosophy behind offensive mine warfare, embracing systems thinking to challenge the traditional objectives of mine warfare and drive the design of a new era of weapons that wait.

**Recommendations for Further Research**

With an understanding of the strategic context, how the naval mine has been used in the past and the current (unclassified) trends for the design of these weapon systems today, this study identified the capability gaps that can be used to inform design alternatives while leveraging many of the opportunities identified as a result of the examination of the problem space. The author contends that offensive mine warfare can be more than simply the psychological deterrence of maritime movements enabled through the threat, real or imagined, to vessels at sea and he invites the U.S. Navy to consider, “what is a mine?” and imagine what other ends may be achievable through technology lurking in the depths. Specifically, further research and development of small, expendable unmanned underwater vehicle platforms, such as the Wreck Interior Exploration Vehicle, especially when thought of as “effects-delivery mechanisms” can help answer that question. Additionally, communications capability, such as short-range underwater electromagnetic signal transmission, through mechanisms such as the Resetting Anchor Antenna Tether Mechanism, expansion of operational capacity outside the water column, and the use of technology to leverage the seabed to change the nature of the battlespace in accordance with the principle of Shi, is recommended.

**References**


Project Summary
Chief of Naval Operations’ (CNO) “NAVPLAN 2021” calls for distributed maritime operations (DMO), littoral operations in a contested environment (LOCE), and expeditionary advanced base operations (EABO) (Chief of Naval Operations, 2021). This project informs DMO, EABO, and LOCE objectives with technical designs for hardware, software, processing, and artificial intelligence/machine learning (AI/ML) at the tactical edge. The hardware evaluation addresses tactical chassis, servers, and networks. The software evaluation assesses cloud software and operations for tactical cloud application development. AI/ML for the tactical edge operating environment is evaluated through a scenario for forward deployed sensor assessment for maintenance, situational awareness, and command decision support. Recommendations are advanced for hardware and software for tactical cloud edge deployments.

Keywords: distributed maritime operations, DMO, littoral operations in a contested environment, LOCE, expeditionary advanced base operations, EABO, naval tactical grid, NTG

Background
Chief of Naval Operations’ (CNO) “A Design for Maintaining Maritime Superiority” calls for comprehensive operational architecture for DMO consisting of (1) a tactical grid to connect distributed nodes; (2) data storage, processing, and technology at the nodes; (3) an overarching data strategy; and (4) analytic tools including artificial AI/ML (Chief of Naval Operations, 2018). This project informs DMO objectives with technical designs for hardware, software, processing and AI/ML at the tactical edge. The Naval S&T Strategic Plan identifies “Warfighter Performance” to ensure readiness through information processing (Office of Naval Research, 2011). System and information processing specifications support officer DMO and EABO qualification. Data was collected and evaluated for DMO, LOCE, and EABO requirements, and for naval tactical grid (NTG), service mesh, electromagnetic spectrum operations, and real time architecture deployment. Metrics were derived from tests on selected hardware and software. Results were developed into decision matrices to inform decision makers.

Findings and Conclusions
This project presented architecture options, hardware and software components for a tactical cloud edge node to support DMO, LOCE, and EABO objectives. The selected micro-service mesh architecture may support NTG objectives. The selected chassis and servers were optimized for tactical deployment with high performance in a low space, weight, power, and cost configuration.
The selected hardware and software combination supports fleet application deployment initiatives with high security architecture in both proprietary and open source configurations.

**Recommendations for Further Research**

Future research may model or prototype the recommended hardware and software configuration for a tactical cloud edge deployment and extend application development for the system.

**References**


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**NPS-21-N095-A: Employing Machine Learning to Predict Student Aviator Performance (Continuation)**

**Researchers:** Dr. Magdi Kamel and CDR Brian Wood USN Ret.

**Student Participation:** No students participated in this research project.

**Project Summary**

For decades, naval aviation training has used the Navy Standard Score (NSS) as the primary means of overall student performance evaluation. Machine learning analysis of student aviator training performance data offers novel and more accurate methodologies than current methods for performance assessment. These methodologies include identifying students for attrition or remediation, as well as identifying optimal pipeline assignments. In a previous effort, we identified important predictors and developed prediction models of performance in primary, intermediate, and advanced training based on data from Aviation Selection Test Battery (ASTB), Introductory Flight Screening (IFS), and Aviation Preflight Indoctrination (API) training. This research extends the effort to later stages of training by developing models to predict performance in advanced training based on earlier stages (Chief of Naval Air Training, n.d.). The goal of the analysis is to determine the set of metrics predictive of student performance for these stages of training and to reveal trends and patterns that may indicate where and when remedial action is needed. The data science methodology used for this research is based on the Cross-Industry Standard Process for Data Mining (CRISP-DM) (Vorhies, 2016). Research results indicate that primary NSS scores alone are not a strong predictor of advanced NSS scores for all pipelines, while intermediate NSS scores are a much better predictor of advanced NSS scores. Further, the research indicates that models for predicting NSS advanced scores based on both primary NSS scores and intermediate NSS scores for pipelines requiring intermediate training are reasonably good ones, with the best models developed for the Jet pipeline.
Finally, the research indicates that the top four candidate predictors for both the average overall and flight advanced event scores are average familiarization, formation, basic, and radio instruments event scores. These results have important implications in reducing time-to-train, improving aviator quality, and reducing training costs related to student failure to complete training.

**Keywords:** machine learning, data analytics, predictive models, aviation training

**Background**
With the current shift within the Navy to new training management systems (i.e., Training Sierra Hotel Aviation Readiness Program [T-SHARP]), new methodologies for evaluating and predicting student performance should be examined. Specifically, machine learning provides an opportunity to better evaluate students by fully examining every indicator of performance throughout a student’s training, from subtest scores on the aviation selection test battery and test scores during initial ground school to each graded item on every flight event. This full integration of performance criteria will identify trends and patterns currently lacking in traditional methods. Specifically, it will provide a better overall evaluation of student success in training, helping to determine which aviation pipeline will ensure the most student success, while highlighting those students needing remediation earlier, in order to provide additional resources.

This research applies advanced statistical and machine learning methodologies and techniques to analyze training data at a more granular level than ever before accomplished. The study also attempts to connect individual-level student data from selection through training to fleet aircraft assignment, providing the opportunity to identify performance indicators and trends across the continuum of aviation training. The data science methodology used for this research is based on the CRISP-DM methodology (Vorhies, 2016). The CRISP-DM process model includes six phases that address the main requirements for data mining. The six phases are undertaken in a cyclical and iterative manner and include: Business/Mission Understanding, Data Understanding, Data Preparation, Modeling, Evaluation, and Deployment.

**Findings and Conclusions**
The main purpose of this research is to provide a data-driven evaluation of student pilot performance to identify performance indicators of whether a student will be successful or not in training, with what type of aircraft and training the student will be most successful, and how early in training can likely success or failure be determined. This will greatly assist Naval Air Training Command sponsor leadership in assigning students the most appropriate training pipeline, as well as identifying individuals for attrition earlier on in training, thus reducing training costs.

Research results indicate that primary NSS scores alone are not a strong predictor of advanced NSS scores for all pipelines, while intermediate NSS scores are a much better predictor of advanced NSS scores. The research also indicates that primary NSS scores are a better predictor of advanced NSS scores for students in advanced Training Wings 4 and 5 for all pipelines, and both primary and intermediate NSS scores are better predictors of advanced NSS scores for students in advanced Training Wing 2 for intermediate training pipelines (i.e., E2/C2, Jet, Tilt-rotor).
Further, the research indicates that models for predicting NSS advanced scores based on both primary NSS scores and intermediate NSS scores for pipelines requiring intermediate training are reasonably good ones, with the best models developed for the Jet pipeline. Finally, the research indicates that the top four candidate predictors for both the average overall and flight advanced event scores are average familiarization, formation, basic, and radio instruments event scores. These results have important implications in reducing time-to-train, improving aviator quality, and reducing training costs related to student failure to complete training.

**Recommendations for Further Research**

In this research effort, we identified important predictors and developed prediction models of performance in advanced naval aviation training based on data from primary and intermediate training. While our methodologies and results provide a good foundation for future research, we recommend extending this effort to later stages of training by developing models to predict performance in the Fleet Replacement Squadron (FRS) based on primary, intermediate, and advanced training. Analysis goals include: determining the set of variables predictive of student performance in FRS; revealing trends and patterns that may indicate where and when remedial action is needed; and identifying in which aviation pipeline a student will be most successful based on performance in preceding training.

**References**


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**NPS-21-N135-A: Information Warfare Force and Systems Readiness Assessment**

**Researcher:** Dr. Randy Maule

**Student Participation:** No students participated in this research project.

**Project Summary**

The education, skills and experience required for information warfare (IW) warfighters have not been fully identified. Nor have training programs been evaluated for their capability to support IW force and systems readiness. This project evaluated Cryptologic Technician - Collection (CTR) and Cryptologic Technician - Technical (CTT) curricula and supporting directives to help structure a methodology for IW systems and warfighter readiness assessment. The research considered Ready, Relevant Learning (RRL) strategies for transition to point-of-need/just-in-time training (United States Fleet Forces Command, 2017), and Advanced Distributed Learning Total Learning Architecture (TLA) for next-generation curricula delivery (Advanced Distributed Learning, 2020). The curricula review advanced IW readiness recommendations to update subject areas and delivery capabilities.

**Keywords:** training, Ready Relevant Learning, RRL, learning management systems, LMS, Total Learning Architecture, TLA
Background
The Naval Science & Technology Strategic Plan “Warfighter Performance” objective addresses (a) training technologies to enhance fundamental information-processing abilities in young adults; (b) techniques to shorten training time, reduce training costs and maximize training impact; and (c) tools and techniques to achieve ubiquitous, engaging, scenario-based training (Office of Naval Research, 2011). In this project, we collected and examined CTR and CTT training curricula as part of the IW modernization initiative. Courses were decomposed into topics by knowledge, skill, and ability (KSA), then into KSA sub-areas by task. Content was reviewed for learning requirements, instructional design, evaluation, and task qualification. Next, the context was decomposed into topics and sub-areas to evaluate knowledge competencies and skill proficiencies.

Findings and Conclusions
CTR and CTT curricula was examined as part of the IW modernization initiative. Recommendations include content updates to address gaps, and new architecture to address Department of Defense (DoD) and Department of the Navy (DON) training and distance training objectives. Results were presented in decision matrices organized by CTR and CTT training competencies across KSA functional areas.

Recommendations for Further Research
Future research may implement the recommendations for training content and assessment updates, and recommended capabilities for more advanced curricula delivery.

References

NPS-21-N167-A: Medical Supply Chain Impacts of Pandemic Preparedness and Response

Researcher: Dr. Douglas MacKinnon
Student Participation: LT Michael Encoy USN

Project Summary
Our efforts sought to address potential personal protective equipment (PPE) shortages to the fleet, the adverse effects to overall readiness, and the preservation of the Navy’s greatest assets, its sailors. Two questions were posed as the study employed an exploratory sequential mixed method research design. The first phase of the research was designed to answer the research question– How can the Navy provide frontline subject matter experts (Independent Duty Corpsman [IDC]) the means to efficiently and accurately track PPEs during COVID-19-type pandemics? For this phase (qualitative), we adopted a case study design leveraging interviews with IDCs.
This resulted in identifying policies related to the governing supply chain. Of equal importance was the identification of an area of deficiency within the IDC’s training curriculum. This inquiry suggests the need for enhanced medical supply chain management training within the didactic level and possible fleet-based training solutions.

The second phase (quantitative) leveraged these findings to inform the stochastic re-order point (ROP) formula with variables to address the second research question– How can the Navy determine a reasonable onboard allowance for pandemic-related PPE given limits on shipboard storage and authorized medical allowance list (AMAL) composition and an empirically-sound prediction for the usage rate of each category of PPE during a pandemic? As some aspects of the qualitative phase yielded limited data, averages and assumptions were made to build and present the proposed stochastic ROP formula to determine a PPE (e.g., N95 masks) safety stock (reasonable onboard allowance) and an ROP. The prepositioned stock scenario resulted in a safety stock of 83 units and an ROP of 244 units. This result suggests a problematic on-hand AMAL requirement as the current guided missile destroyer (DDG) assemblage requirement is only 120 units yet represents an inventory level to sustain on-hand stocks to prevent future PPE stockouts.

Keywords: COVID-19, pandemic, supply chain, optimization, pre-positioning, personal protective equipment, PPE, re-order point, ROP

Background
We begin this research by explaining the demand and purpose for the current study by first presenting historical, comparative, and epidemiological pandemic data and the current impact of COVID-19 on the population’s health and socioeconomic implications. We then narrow our scope focusing on subject matter experts (IDCs) within the Arleigh Burke-class DDG platform, concentrating on optimizing the PPE (N95) supply chain. We examined COVID-19 response at the ship and fleet levels by evaluating notional modifications to authorized medical shipboard allowances and medical supply chain processes and policies to increase resiliency for future pandemics. To accomplish this, policy data was gathered related to the required shipboard AMAL, including consumable supplies, which are presently tailored toward mass casualty situations and not pandemics. Guidance from the Office of the Chief of Naval Operations, Pacific Fleet, Fleet Forces, and Navy Medicine guidance regarding pandemic preparedness and response was also examined. The initial findings were then integrated with the AMAL review processes. The data were brought together with Commander, Naval Surface Forces, Pacific Fleet After-Action Reports and lessons learned from the COVID-19 pandemic to understand likely usage rates and on-hand inventory.

The research sought to address potential PPE shortages to the fleet, the adverse effects to overall readiness, and the preservation of the Navy’s greatest assets, its sailors. In addressing this, two questions were posed as the study employed an exploratory sequential mixed method research design. The first phase of the research method was designed to answer the first research question– How can the Navy provide frontline subject matter experts (IDCs) the means to efficiently and accurately track PPEs during COVID-19 type pandemics? This first phase (qualitative) adopted a case study design leveraging interviews with IDCs. The case study design used here is one of the most widely used research methods across academic realms (Yazan, 2015). Case studies focus on collecting data through inquiries or evaluations of programs, activities, processes or events (Creswell, 2014) over a period of time (Yin, 2012).
This design selection is appropriate for the current study due to its qualitative component’s inquiry into the IDCs’ activities and processes as they maintain medical supply inventory.

The second phase (quantitative) took elements from the first phase’s interview results to inform the stochastic ROP formula with variables to address the second research question– How can the Navy determine a reasonable onboard allowance for pandemic-related PPE given limits on shipboard storage and AMAL composition and an empirically-sound prediction for the usage rate of each category of PPE during a pandemic? As some aspects of the qualitative phase yielded limited data, averages and assumptions were made to build and present the proposed stochastic ROP formula to determine a PPE safety stock (reasonable onboard allowance), and a re-order point. The model of the ROP, where variable (random and unknown) expenditure rates and lead times are accounted for, unlike a standard deterministic model, reflect known and constant expenditure rates and lead times (Maiti et al., 2009).

Findings and Conclusions
The IDC interviews resulted in identifying positive attributes of base knowledge of understanding available sources of policies related to supply chain. Of equal importance was the identification of an area of deficiency within the IDC’s training curriculum. This implication elicited the recommendation of enhanced medical supply chain management training within the didactic level and possible fleet-based training solutions.

The prepositioned stock scenario resulted in a safety stock of 82.46 units and an ROP of 243.46 units. This result suggests a problematic on-hand AMAL requirement as the current DDG assemblage requirement is only 120 units. The second scenario, cross-level support, resulted in a safety stock of 80.39 units and an ROP of 87.29 units. Although this scenario resulted in a feasible outcome, this replenishment option is not ideal and should only be executed in contingent or emergent situations. This phase addressed the study’s second research question and offered reasonable onboard allowances in two different scenarios. The proposed safety stocks resulting from the stochastic ROP formula may provide DDGs an inventory level to sustain on-hand stocks while preventing PPE stockouts in future pandemics.

As a result of the mixed-method exploratory sequential design, the recommendations we offer include the establishment of accurate PPE tracking standards, employment of an automated ROP model, sustainment of the AMAL periodic review process, and the enhancement of supply chain training solutions for IDCs.

Recommendations for Further Research
Future research should be considered to build upon the results from the current study and enhance the Navy's resilience in potential pandemics. With a continued focus on medical supply chain, studies pertaining to other ship classes such as landing helicopter attacks (LHAs), landing helicopter docks (LHDs), and nuclear-powered aircraft carriers (CVNs), and submarines should be considered. A vital accessory to platform-specific studies are studies that focus on personal protective equipment (PPE) supply procurement. More specifically, studies that aim to determine optimal stockpiling and pre-positioning schemes should be considered to emphasize assured access and prompt replenishment to underway fleet assets. Studies such as these could be further complemented with research aimed at leveraging technological innovations involving forecasting methods to optimize PPE assemblage requirements that inform notional authorized medical allowance lists (AMALs).
Another relevant area of study to consider may be the potential price gouging of PPEs, as their use proliferated in the COVID-19 era. An area to consider would be how to establish dedicated stocks impervious to national or international stock shortages and regulation of prices while securing procurement solutions economically beneficial to the Department of Defense.

Lastly, as vaccine data is gathered, there may be high demands for studies identifying obstacles and leveraging solutions for efficient means of distribution across the fleet. Such studies might take into consideration the effects of vaccine stock and efficacy as COVID-19 variants arise. Contingency supply chain planning should still be emphasized across the fleet to ensure readiness across the fleet and perhaps even extend to all branches of the military. Current processes involve Naval Medical Logistics Command and content managers such as the Commander-Fleet Forces, Command Surgeon, and the Type Commander Surgeon, who offer annual reviews of AMAL composition across the fleet where subject matter experts participate in an annual November time frame conference to discuss changes (allowance change requests). Discussions are based on thoughtful insight from subject matter expert experience and scholarship regarding medical care and how to leverage the supply chain. Theoretically grounded automated innovations might aid in a more standardized method of forecasting individual needs of commands and platforms.

References

NPS-21-N188-A: Analysis: How to Rapidly Bring Hypersonic Missile Capability to the Surface Fleet

Researchers: Dr. Eugene Paulo, Dr. Paul Beery, and Dr. Wayne Porter CAPT USN Ret.
Student Participation: Ms. Thia Tank CIV, Mr. Sebastian Banuchi CIV, Mr. Cole Rice CIV, and Mr. Thomas Hughes CIV

Project Summary
As of 2021, the U.S. does not have a hypersonic weapon in its arsenal to counter Chinese and Russian hypersonic weapons already deployed in the battlefield. The Naval Surface and Mine Warfighting Development Center (SMWDC) proposed a study to examine multiple Navy surface ship platforms and perform analysis of how to bring hypersonic missile capability to the surface fleet by FY 2025. While the Navy is conducting ongoing testing of its version of a hypersonic missile, there is a need to examine launch methods for these missiles from existing surface ships in the near future.
The ability to successfully launch hypersonic anti-ship missiles, as well as hypersonic missiles in support of land forces, could provide significant advantage to joint forces. This project developed three candidate systems that describe possible integration of the Army's Long-Range Hypersonic Weapon (LRHW) system before the Navy's Conventional Prompt Strike Program is operational.

Three types of vessels considered for the candidate systems were: 1) amphibious transport dock (LPD) class vessel, LRHW with trailer launch; 2) Expeditionary Fast Transport (EPF) class vessel, LRHW All-Up-Round (AUR) with crane launch; and 3) littoral combat ship (LCS) class vessel, LRHW with trailer launch. Analysis was conducted using the multi-attribute value theory and focused on these three attributes: 1) number of AURs stored; 2) time to implement hypersonic launcher on board vessel; and 3) time to execute launch. Candidate system 1, LPD, scored highest when evaluated based on all three attributes. We therefore recommend LPD be considered as a possible ship platform for future hypersonic glide body weapon system with additional in-depth studies, modeling, and analysis needed to explore the use of box launchers, LPD trade-offs, and fleet planning around the new hypersonic missile capability.

**Keywords:** hypervelocity missile, hypervelocity missile ship launch platform

**Background**
Considering the military and technological advances in hypersonic weapons development of the Chinese in recent years, the U.S. Joint Forces face a considerable challenge to counter with hypersonic weapons of their own. The Navy's conventional prompt strike currently does not include hypersonic weapons as part of its arsenal. While the Navy is conducting ongoing testing of its version of a hypersonic missile, there is a need to examine alternative launch methods for these missiles from a variety of existing surface ships in the near future. The ability to successfully deploy and launch hypersonic anti-ship missiles, as well as potentially hypersonic missiles in support of land forces, could provide significant advantage to joint forces.

This study leveraged experience gained by applying systems engineering and systems architecting to our recent projects involving the operational Navy and missions at sea that consider new technologies (including Sea Hunter, an unmanned surface vessel, as well as Railgun) and emerging operational concepts (such as distributed maritime operations). The approach allowed for system design decisions to be made based on the feasibility of the design of a hypersonic missile launch system in the physical domain, but also demonstrated its potential contribution to the operational domain through the demonstration of added mission effectiveness. The literature review for this project focused on describing the current capabilities and attributes of the ships that could be used or modified to achieve additional hypersonic missile capabilities, the current capabilities of the non-hypersonic missile systems that these vessels are equipped with, and finally the likely attributes of the hypersonic missiles that could be equipped on the vessels. The vessels and hypersonic missiles were combined in a variety of ways to create candidate systems for achieving the hypersonic missile capability. The research performed on the vessels and weapons systems that could be used to achieve the goal of rapidly equipping a surface vessel with a hypersonic strike capability, indicates that there is the potential for several different combinations of candidate systems.
Research into the Army’s LRHW system has shown that the LRHW is currently the most mature hypersonic glide body system developed by the DoD and could potentially be integrated onto various vessels to deliver a hypersonic glide body capability to Navy surface ships. This research team developed three candidate systems, using different launch platforms, that describe a possible integration of the LRHW system before the Navy’s Conventional Prompt Strike Program is operational. The three types of vessels considered for the candidate systems were: 1) LPD class vessel, LRHW with trailer launch, 2) EPF class vessel, LRHW AUR with crane launch and 3) LCS class vessel, LRHW with trailer launch. The four primary areas of operational activity were identified as storing missiles, preparing missiles for launch, launching the missiles, and retrograding the launcher.

Findings and Conclusions
The research questions that are addressed throughout this project can be broadly placed into three different categories:

1. Can a system be developed that safely, effectively, and efficiently stores, transports, and launches hypersonic missiles from existing Navy platforms using launch methods that are not currently employed? How can this system accommodate the use of other established missile systems?
2. Which design considerations of the alternative launching system are the most critical to the successful implementation of this offensive strike capability?
3. What are the strategic advantages offered to the fleet by the successful implementation of the offensive strike system described?

The operational activities stated in the previous section are directly related to primary attributes identified and analyzed, which were: 1) number of AURs stored; 2) time to implement hypersonic launcher on board vessel; and 3) time to execute launch. System analysis that considered these attributes and addressed these research questions was conducted using the multi-attribute value theory. This approach allowed for the assessment of all attributes with a combination of stakeholder preferences over conflicting attributes to discover alternatives with the highest value. Only the genuine distinctions between alternatives were used to make decisions. Focusing on the differences between alternatives provided attributes that would offer the strongest justification during our decision evaluation. To appropriately measure three independent criteria within an additive model we determined swing weights for each attribute, which allows for the individual values to be measured together although they do not have similar units. After performing the swing weights analysis of all three attributes, Candidate system 1, LPD, scored highest when evaluated based on all three attributes. Close behind was Candidate system 3, LCS, while Candidate system 2, the EPF, lagged behind considerably. We therefore recommend Candidate system 1, LPD, be considered as a possible ship platform for future hypersonic glide body weapon system.

Recommendations for Further Research
Additional in-depth studies, modeling, and analysis should be conducted to explore the use of box launchers, amphibious transport dock (LPD) trade-offs (specifically regarding the role of a marine assault force and displacement of some of its equipment if hypervelocity missiles are on board), and fleet planning around the new hypersonic missile capability. There should also be studies considering ways to more safely store these missiles on every ship.
NPS-21-N213-A: Quantifying, Visualizing, and Tracking Capability Gaps

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

Project Summary
While numerous sources of information identify warfighting capability gaps and/or provide recommendations to close gaps and/or provide new/improved capabilities to the fleet, no comprehensive system, and responsible entity, captures all of that information in one place to provide a clear and concise picture of progress being made to close identified gaps and/or provide a capability. To address this problem, we developed in a previous effort, a methodology based on Multi-Criteria Decision Analysis (MCDA) methods to calculate and visualize a capability gap score at any given point in time to depict capability gap resolution progress across the elements of the Doctrine, Organization, Training, Materiel, Leadership, Education, Personnel, and Facilities (DOTMLPF) framework and based on substantiated real-time information. In this effort we expand the DOTMLPF framework used to evaluate capabilities by adding new elements and sub-elements and extend the MCDA methodology by incorporating different models for calculating the capability gap score. These models include the Weighted Sum Model (WSM), the Weighted Product Model (WPM), the Weighted Aggregated Sum Product Assessment (WASPA), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Analytic Hierarchy Process (AHP).

The goal of the effort is to develop a comprehensive methodology that would enable Navy leadership to have a clearer picture of what has been accomplished, what remains to be done, who has action, and the critical path to closing the gap and/or delivering a capability.

Keywords: gap analysis, Multi-Criteria Decision Analysis, MCDA, data visualization

Background
Myriad sources of information identify warfighting capability gaps and/or provide recommendations to close gaps and/or provide new/improved capabilities to the fleet. Sources that identify gaps include Warfighting Development Center Integrated Prioritized Capability Lists (IPCL), Combatant Commander Integrated Priority Lists, Navy and Joint Urgent Operational Needs Statements, Chief of Naval Operations Key Operational Problems, Navy and Joint Lessons Learned database, to name just a few. Sources that identify findings and recommendations addressing gaps include final reports of Navy and Joint war games, Fleet Experimentation program, Navy and Joint studies, Center for Naval Analysis studies, exercise after action reports, Navy and Joint Lessons Learned database, post-deployment briefs, etc. What appears to be missing is a comprehensive system, and responsible entity, that captures all that information in one place to provide a clear and concise picture of progress being made to close identified gaps and/or provide capability. To close a given gap or deliver a new capability requires action at multiple levels across the DOTMLPF spectrum. Without a comprehensive system to track all that action, Navy leadership does not have a clear picture of what has been accomplished, what remains to be done, who has action, and what is the critical path to closing the gap and/or delivering the capability. The methodology used for this research is based on multi-criteria decision making (MCDA) methods that consists of the following steps (Parlos, 2000): 1) Determine the relevant criteria and alternatives of a decision problem, 2) Attach weights
that reflect the relative importance of the criteria on decision, 3) Rate the alternatives with respect to the criteria, and 4) Process the weights and ratings to determine a ranking of each alternative.

Findings and Conclusions
In this research effort, we extended the MCDA methodology, developed in a previous effort and used to calculate capability gap scores. The extended methodology consists of the following steps: 1) Identifying factors that influence a capability gap using an appropriate capability framework, 2) Rating capabilities on identified factors, 3) Assigning weights to identified factors, 4) Calculating a capability gap score from ratings and weights using an appropriate MCDA model, 5) Conducting a sensitivity analysis to evaluate how other ratings and weights affect the capability gap score, and 6) Visualizing capability gap scores across time and factors using a dashboard. The extended methodology uses different models for combining factor weights and capability ratings to calculate a capability gap score. These models include the Weighted Sum Model (WSM), the Weighted Product Model (WPM), the Weighted Aggregated Sum Product Assessment (WASPA), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Analytic Hierarchy Process (AHP). We also expanded and extended the DOTMLPF framework used to evaluate capabilities by adding new elements and sub-elements to the framework. We applied the developed methodology to a scenario of three programs to demonstrate the viability and applicability of the approach.

The result of the research is a comprehensive methodology that can be used to 1) support prioritization of capabilities based on hard data, 2) provide a clear and concise picture of progress being made to close identified gaps and/or provide a capability, and 3) support the creation of a central repository for organizations to distribute pertinent information.

Recommendations for Further Research
For future research efforts, we recommend continuing to refine the Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) capability management framework by adding new and/or modifying existing elements and sub-elements as appropriate. We also recommend applying the proposed methodology to several real-life capability scenarios and visualize the resulting gap scores across time and framework factors. Finally, we recommend developing a comprehensive dashboard, with a rich set of graphs and charts, to provide decision makers with an at-a-glance view of the status of each program across time and elements of the DOTMLPF framework.

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NPS-21-N263-A: High Data Rate HF Communications for BFTN using Advanced Waveform Techniques

Researchers: Dr. Ric Romero, Dr. Douglas Fouts, Ms. Donna Miller, and Mr. Robert Broadston
Student Participation: LT Larry Pineda USN

Project Summary
This project investigates the feasibility of utilizing advanced waveform techniques such as orthogonal frequency division multiplexing (OFDM) coupled with constant energy modulation (CEM) to achieve high data rates in high frequency (HF) communications that can be used for the Battlefield Tactical Network (BFTN) framework. Advanced waveform techniques mitigate various propagation issues with long-range HF communications systems. Thus, HF employing increased data rates may be a viable alternative when a satellite communications (SATCOM) system is degraded. With the use of computer simulation (e.g., Matlab), we find that it is feasible to transmit high data rate advanced waveforms. Moreover, we find that cognitive radio (CR) sensing techniques mitigate HF propagation issues by avoiding degraded frequency bands and by utilizing good frequency channels. We find that the proposed techniques yield symbol error rates (SER) or bit error rates (BER) comparable to that of traditional digital HF modulation such as frequency shift keying.

Keywords: high frequency, HF, satellite communications, SATCOM, orthogonal frequency division multiplexing, OFDM, constant energy modulation, CEM, Battlefield Tactical Network, BFTN, cognitive radio, CR, bit error rate, BER, symbol error rate, SER

Background
SATCOM systems provide important real-time communications for civilian and military purposes. However, in degraded SATCOM situations, a viable long-range alternative is needed for critical defense purposes. Here, we investigate the use of HF communications as a viable alternative.

While HF is indeed a very good long-range alternative, it is well known that HF frequencies (3-30 MHz) experience various propagation issues, which result in very degraded voice/audio quality or large error rates in terms of data communications. Moreover, HF channels are very limited due to other uses allowed by the international community, such as amateur radio or the so called “HAM” radio bands. For example, a typical channel spacing is 3 KHz while the maximum allowed is 48 KHz. Our goal in this project is to propose viable solutions to mitigate the degraded channel gains caused by propagation issues. Another goal is to show that advanced digital waveforms can be used for high data rate HF instead of the older analog and digital modulation techniques.

To mitigate degraded channel states caused by HF propagation issues, we take advantage of ample CR mitigation techniques such as the well-known waterfiling and ad-hoc gain inversion (AGI) techniques, both of which are well illustrated in (Parmentar et al., 2019). The technique we propose here is a simplified version of both techniques above. As for increasing the data rate, we propose the use of CEM alongside OFDM, which are discussed in (Romero et al., 2019).
Findings and Conclusions
In this project, we proposed to mitigate the HF channel state issues due to propagation issues and even noise jamming issues with the use of a simplified mitigation technique based on waterfilling and AGI. We also proposed the use of CEM-OFDM to increase the data rate.

We found that the combination of gain mitigation technique and the CEM-OFDM modulation mitigated the degraded channel states. Moreover, it was shown that the BER and SER were decreased in the presence of either propagation interference or correlated jamming noise. The details of these techniques and results will be published in the thesis of the student helping this project. LT Larry Pineda is projected to graduate in December 2021 and will report the technical details and results of this feasibility study.

We believe that with the use of advance digital waveform techniques along with the channel gain mitigation techniques above, HF communication systems can be improved both in terms of increased data rate and BER/SER. This finding potentially shows that HF communications systems can be viable alternatives to SATCOM.

There is a resurgence of research and development activities around HF not only in various outfits of the Department of the Navy (DoN) such as Naval Information Warfighting Development Command but in all the branches of Department of Defense. Indeed, there is a large representation from all services in the HF Working Group which meets to discuss improvement to HF systems. It would behoove the group to look into digital techniques such as the ones presented here.

Recommendations for Further Research
It is recommended to look into implementing advanced waveform techniques such as constant energy modulation (CEM) coupled with orthogonal division frequency multiplexing (OFDM) in actual hardware implementation of high frequency (HF) systems. Furthermore, it is recommended that the hardware implementation be tested in the field. In other words, HF systems employing these techniques in transmitters and receivers should be tested with actual waveform transmissions preferably in long-range situations to validate the channel state mitigation with transmission beyond 3 KHz and perhaps transmission at 48 KHz and beyond.

References
**NPS-21-N264-A: Joint Fires Seabed Warfare**

**Researcher:** Dr. Shelley Gallup  
**Student Participation:** No students participated in this research project.

**Project Summary**  
Seabed warfare is quickly being realized as an important dimension of modern warfare. However, there are many difficulties associated with this domain. There are technical challenges that come with the undersea environment, logistical problems serving the technical dimension and communication, and information systems difficulties, just to name a few. At a higher level, seabed warfare encompasses a systems of systems (SoS). Each part of the system must work together so that the process of tasking, collection, processing, exploiting, and dissemination (TCPED) can include this domain. Generally, TCPED results in important decision making within the joint fires process, and in a Joint Targeting Folder. The intelligence community is particularly involved in receiving and sense making of data from this domain, and in this project, we look at the production and flow of acoustic intelligence (ACINT) as it progresses through a myriad of intelligence organizations and becomes data at rest for historical purposes or is included at the decision level of TCPED. This is new territory for the intelligence community. Here we look at the knowledge needs of the operational community for the data being produced and follow those needs through organization structures. The first part of this project identified the structures, and a continuation of this project includes use of Monterey Phoenix to find emerging behaviors as intelligence is further tasked to provide data that will support decision making at the level of the Joint Task Force Commander. The bulk of this research is at the SECRET level. Research questions include: What are current practices for Joint Targeting? Are there commonalities between undersea warfare/seabed warfare and the joint fires process? With respect primarily to acoustic intelligence, how will this information contribute to the Joint Task Force Commander in execution of joint fires decision making?

**Keywords:** seabed warfare; tasking, collection, processing, exploitation, and dissemination; TCPED; intelligence community; Joint Targeting Folders; Joint Task Force Commander; Monterey Phoenix; emergent behavior

**Background**  
Seabed warfare is now recognized as an important dimension to fighting in a joint theater-level environment. Current processes for assessing and assigning targets rapidly (such as target selection, third-party targeting, and post-strike bomb hit assessment) are well understood in aviation warfare in a joint environment. This planning and information flow have potential applicability to the undersea environment. Joint commanders routinely require targeting-quality information (whether imagery or, in the case of seabed warfare, high-resolution acoustic) and associated metadata for decision making. Adapting current practices (e.g., TCPED) and mechanisms and procedures for providing timely and accurate servicing with joint fires are immature. This research project will investigate and analyze current practices and requirements that include the new technical capabilities that enable seabed warfare, and the distribution of information through planning practices. Products of research will allow the Joint Task Force Commander to employ joint fires more effectively against seabed targets and will aid in facilitating the flow of critical targeting information to non-naval strike assets. The research will first focus on current procedures for conducting joint seabed warfare, specifically on data flows, and compare them with the
joint fires processes in use at present. In current practice, joint fires folders are created. How will joint seabed warfare be included in Joint Targeting Folders? Finally, what are the sensitivities of these processes to communications degraded environments? Products will include highly developed systems view of current and future information distribution into processes used in joint targeting with recommendations for improvements to information flows, data needs and decision processes in joint fires to create intended effects in the seabed environment.

**Findings and Conclusions**
The research was conducted at the SECRET and occasionally at the TOP SECRET levels as it involves the means and capabilities of the intelligence community around acoustic intelligence. However, at the UNCLASSIFIED level, a review of joint targeting processes such as the Joint Targeting Handbook and a contractor provided flow diagram of the processes involved, organizations and operations revealed little cross connections between acoustic intelligence and the joint targeting system. Analogs of joint fires as found in the aviation community, which is very mature, provide some direction of what a set of processes and procedures in the future might be. However, implications exist for changes at the intelligence processing level: a cultural shift, additional means for communicating information, and inclusion of the seabed in current doctrine.

The findings so far are incomplete. The actual system under research does not exist. What does exist is a current system that is well tuned to the needs of the past, but not the future. What is most likely is that instead of re-writing the entire community around acoustic intelligence is to find the “exit ramps” for specific information that is at the operational level and useful in creating targeting folders. To aid in finding these “off-ramps” the computer event simulation Monterey Phoenix will be used, requiring a stand-alone laptop to be loaded and maintained as a SECRET level asset in the Secure Technology Battle Lab. The current system of interrelated organizations and their dependencies will be the first priority, to be followed by excursions to “what if.”

**Recommendations for Further Research**
Additional assets will be needed to parse a very complex system into its parts, interrelations, dependencies, requirements and insertion into the joint targeting environment, itself a complex system. As simulations of these relationships mature, it is proposed that a refined view of the data, its paths, and needs for targeting that include the seabed will come into further focus. Further elaboration is needed with regard to the actual needs and usage of the current data flows, which are very ambiguous.

**References**
NPS-21-N281-A: Navy Expeditionary Additive Manufacturing (AM) Capability Integration

Researchers: Dr. Douglas Van Bossuyt and Dr. Amela Sadagic
Student Participation: Ms. Leslie Amodeo CIV, Mr. Brian Dick CIV, Mr. Charles Flynn CIV, Ms. Rebecca Nagurney CIV, and Ms. Meagan Parker CIV

Project Summary
This project analyzed the current and future use of additive manufacturing (AM) technologies within the Department of Defense (DOD) and specifically for Naval Expeditionary Forces. This analysis provided the technical background necessary to develop a pilot software tool dubbed the Additive Manufacturing Process and Analysis Tool (AMPAT). With further development and augmentations, AMPAT could help stakeholders identify what AM equipment best serves warfighters and their missions in expeditionary environments. Furthermore, the stakeholders can use the tool to identify the most advantageous dispersions of AM capabilities across the fleet and make decisions on how those capabilities should be integrated into the greater naval mission and larger DOD enterprise. To support the work on this effort, our project team designed and implemented a systems engineering (SE) approach to gather information on current and prospective AM methods and understand and define the AM system operational requirements. Additionally, the SE process was utilized to analyze alternative off-the-shelf software options to build the tool and verify and validate that the tool met the project requirements. The project determined that AMPAT allowed users to enter information about 3D printers, expand that list as new printers become available, and successfully generate a ranked list of AM systems recommendations based on user-defined input parameters and weighting values. Recommendations for choosing AM equipment and developing dispersion plans for the fleet include using the AMPAT deliverable to conduct customized, iterative analysis with user-defined inputs that are tailored to specific expeditionary environments.

Keywords: additive manufacturing, 3D printing, Naval Expeditionary Forces, distributed maritime operations, DMO, littoral operations in contested environments, LOCE, expeditionary advanced base operations, EABO

Background
For several years, the Navy and Marine Corps have been employing AM capabilities in operational environments to rapidly deliver parts, tools, and equipment needed to support the mission of the warfighters. As the landscape of AM solutions became more diverse with time, the naval community also identified a need for a study that would determine how to integrate future AM capabilities while maximizing return on investment and minimizing duplicated efforts. The overarching objective is for the results of this project to be further matured and then applied to capabilities deployed in various environments such as distributed maritime operations (DMO), littoral operations in contested environments (LOCE), and expeditionary advanced base operations (EABO). This project focuses on the design and development of a pilot tool and associated database schema to assist decision makers in determining the appropriate AM to use within these environments.
AM technology has been proven to be highly beneficial by providing reduced fabrication costs and fast component replacement and repair. Because AM is a rapidly advancing technology field, it is difficult to consistently compare and weigh technology capabilities and attributes to meet the ever-changing needs of its end users. A specially designed tool is needed to provide Navy leadership well-based insights into what capabilities the current and new AM technology provide; that information is further used to make informed decisions on how to maximize the return on investment for the DOD in support of the warfighters and their missions. Some characteristics that needed to be considered for decision-makers included mobility, ease of use, training, type of printing material, and printer bed size.

The purpose of this project was to provide an overarching decision analysis method and pilot tool that included an easily modifiable database populated with a representative sample of current 3D printers and parts for the Naval Expeditionary Combat Command (NECC); the tool had to support an efficient integration of current and future AM capabilities into the broader Navy expeditionary mission. The project team researched current AM capabilities and their applications for expeditionary forces to help develop the analysis method, pilot tool, and database that NECC could adopt and use to best determine how to disperse AM resources and maximize benefits across the U.S. Navy fleet. While there is a broad need and great potential for AM integration within the Naval Expeditionary Forces and broadly within the Navy and DOD, the project focused on AM as a supportability capability for deployed systems, platforms, and vehicles. Ultimately, this plan was designed to serve as a reference guide for the NECC to make informed decisions concerning AM equipment deployment strategies and acquisitions for the Navy and Marines.

**Findings and Conclusions**

The use of AM technology is growing rapidly throughout the Department of the Navy (DON) and DOD. The main objective for the deployment of this technology is to ensure an increase in readiness while providing sustainment and enhancing global warfighting capabilities. Currently, the DOD uses different user-friendly, low-cost commercial off-the-shelf (COTS) AM printers to expedite the procurement process for a variety of parts and decrease the length of training time on the part of the operators. As a result of the nonconformity of AM systems across the DOD, inefficiencies are more likely to occur, such as redundant training, false assumptions, and increased user errors. The results of this project and insights that the team members acquired can help align the DON and DOD to progress AM technology in a unified effort and support the needs of the greater naval mission.

The analysis performed using the pilot tool can be applied to a range of scenarios, including large-scale missions aboard amphibious ships to smaller, tailored missions constrained to specific attributes. The pilot tool empowers the user to conduct customized, iterative analysis with user-defined inputs tailored to a specific use case.

A set of research efforts designed to support project objectives fulfilled the purpose and addressed the research questions identified for this project. The team provided the NECC with an easy-to-use pilot tool and decision-making process, allowing decision-makers to recommend specific AM equipment on deployed systems, platforms, and vehicles in various environments including DMO, LOCE, and EABO. Although this project was purposefully constrained to the unclassified level, the pilot tool can be used in higher classification environments with inputs that are tailored to specific locations and mission needs.
Lastly, analysis run through the pilot tool can be used to justify DOD approval decisions for AM equipment, which would help the NECC integrate its capabilities into the greater Navy mission. The project team also made a conscious effort to connect with colleagues throughout the Navy to ensure other groups could leverage the insights and results of this work. The AMPAT tool, a textual manual, and a video manual created in this project are made available to the topic sponsor and other colleagues in the naval domain.

**Recommendations for Further Research**

Research efforts made in this project represent only a starting point to a much larger body of work that needs to be done in the Additive Manufacturing (AM) domain. Additional work is required to refine and expand upon the project and pilot tool to maximize the benefits to the Department of Navy (DON) and Department of Defense (DOD). We identified a set of follow-on efforts as a representative work that should be done in the future:

- Material properties should be added as an attribute to the pilot tool to allow users to identify the best AM design and support materials that could be used against degradation or corrosion.
- AM resources from all branches of the DOD should be added to the pilot tool database. That will minimize duplication of efforts and maximize return on investment for specific AM systems.
- The pilot tool should be up-domain to a higher security classification environment and allow for use of controlled unclassified information (CUI) and/or classified inputs. This would permit for more comprehensive analysis pertaining to specific locations in the fleet to make informed decisions about prepositioning of AM equipment.
- The pilot tool should be used to conduct analysis and recommend AM systems and resources capable of supporting more advanced maintenance, such as depot-level repair or construction operations. While the scenarios in the project focus on using AM systems to build replacement parts, there is also interest within the DOD to use AM as much as possible for major repairs and overhaul.
- In addition to the representative AM technology database in the pilot tool, the pilot tool should be expanded upon to include a library or repository of parts and part specifications. That would expand the utility of the pilot tool and allow it to make recommendations for AM systems that should be used to print specific parts to support ships, submarines, aircraft, and other vehicles or equipment.
- The DOD should investigate the integration of the pilot tool with the Additive Manufacturing Cost Analysis Tool (AMCAT), developed and maintained by Naval Supply Systems Command. AMCAT provides users with a cost analysis for the price of procuring a part vs. the price of printing a part with AM technology. AMCAT also has the potential to aggregate metrics based on collected data, such as usability and reliability attributes. The integration of the pilot tool and AMCAT has the potential to provide the DOD with a powerful, all-encompassing tool that can provide technical and cost analysis of AM systems and parts to fulfill specific operational missions.

A configuration management plan or program should be developed to keep track of the most current version of the pilot tool. As the tool will be delivered to multiple organizations and users, it would be most beneficial to have a process in place to ensure that all modifications and additions are accessible by all stakeholders.
NPS-21-M140-A: Analysis of Alternative UAV Technologies to Support Next-generation UAV

Researchers: Dr. Anthony Pollman Capt USMC Ret., Dr. Anthony Gannon, and Dr. Walter Smith
Student Participation: LT William Melton USN

Project Summary
Unmanned aerial vehicles (UAV) are strategic tools that boast immense capability; however, these systems are still limited by the logistical demands of fuel production and fuel supply. Naval Air System Command (NAVAIR) and Naval Research Laboratory (NRL) are in search of a capability that would allow unit-based production of hydrogen fuel for hydrogen fuel cells for a next-generation, fixed wing, hydrogen fuel-cell UAV. Electrolyzers are the clear answer to this problem. Electrolyzers produce hydrogen and oxygen from water using electricity and are widely used by the United States Navy (USN) submarine service as oxygen generators. This research explored all currently qualified electrolyzer systems in the USN, determined the relevant functional and performance parameters, and developed the most advantageous use-cases from the qualified candidate electrolyzer systems.

The Navy currently uses three qualified oxygen generators: the Low Pressure Electrolyzer (LPE), the Integrated Low Pressure Electrolyzer (ILPE), and the Automatic Electrolytic Oxygen Generator (AEOG). This research utilized the model-based systems engineering methodology for employing architecture for systems analysis (MBSE MEASA) in concert with Systems Modeling Language (SysML) to synthesize the requirements from the sponsors into a working architecture that informed the selection of the most preferred functional and performance criteria of the desired system. The culmination of this methodology was a multi-criteria decision-making (MCDM) model based on the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodology to aid in a system selection recommendation.

The MCDM model resulted in the unanimous selection of the LPE over the other alternatives for all use-cases and each iteration of the model. In continuation of this work, it is recommended to analyze the functional and performance criteria using other forms of multi-criteria decision-making models to verify and validate the results. Additionally, commercial off-the-shelf (COTS) options should be considered regardless of qualification status.

Keywords: unmanned systems, hydrogen fuel cell, electrolyzer, energy optimization, logistical independence, Systems Modeling Language, SysML, model-based systems engineering methodology for employing architecture for systems analysis, MBSE MEASA

Background
UAVs are a force multiplier on the battlefield in a multitude of diverse and strategic ways. They enable the operational commander as well as the civilian user to extend their reach with a high level of fidelity without many of the risks that traditional aviation poses to human life. NRL successfully designed, built,
and operated the Ion Tiger hydrogen fuel cell UAV, which set unofficial endurance records for fuel cell powered flight by flying for 26 hours while carrying a five-pound payload (Swider-Lyons et al., 2010). Building on experience with the Ion Tiger UAV, NRL is developing prototypes for the next generation fuel cell UAV. A key requirement for the next generation design is the use of a fuel that does not require its own logistics; therefore, electrolyzers, which generate hydrogen fuel from water using electricity, are being explored as a sustainable and logistically independent fuel supply system. Additionally, the electrolyzer must already be qualified for use by the USN.

According to Pollman (2013), “Exponential equipment and capability growth has made us much heavier and much less agile. This equipment growth has come with a commensurate growth in fuel and energy consumption, which ties us to long and vulnerable logistics trains. Our enemies have recognized and successfully exploited this vulnerability” (p. 69). This study aims to link a desired capability of a hydrogen fuel cell to a fuel production method as a system to minimize the logistical burden on the units who operate the system. Additionally, this research is an exercise in utilizing an established method for going from stated requirements to needs, employing an architecture, determining relevant parameters and criteria, and utilizing a model or analysis method to aid in decision-making.

This research utilized the MBSE MEASA process to distill the needs and technical desires of NRL and NAVAIR into clearly defined requirements and subsequently used SysML to transform the requirements into a functional and physical architecture. According to Beery (2016), “The functional architecture specifies what the system must do to satisfy the developed requirements and the physical architecture specifies what system components are necessary to perform the functions identified in the functional architecture” (p. 7). The above represents the first three steps of the MBSE MEASA process. The output of the first three steps of the MBSE MEASA process is a set of critical technical parameters that are then distilled into criteria as the inputs for the MCDM model. Each criterion is given a weight factor based on a unique use case which serves as a preference for one factor over another.

This work directly supports the analysis and assessment needs of Headquarters Marine Corps, Aviation and the Office of the Chief of Naval Operations N94. It also answers the Chief of Naval Operation’s call, spelled out in A Design for Maintaining Maritime Superiority 2.0, to better leverage the Naval Postgraduate School to address long term sustainment and logistics in support of the Distributed Maritime Operations concept (United States Navy, 2018).

**Findings and Conclusions**

This research implemented the MBSE MEASA process to develop a functional and physical architecture from the sponsors’ needs and requirements. The output of the architecture was a set of measurable system parameters that are the input criteria for the MCDM model. Additionally, the requirements analysis resulted in three mission options, or operational settings, in which the system could be used. The first mission option conceptualizes a ship-based system, where it is tied to and derives its power and resources solely from the ship. The second mission option utilizes the system in concert with a mobile unit, either on-foot or as the payload for a multi-purpose vehicle, such as a high mobility multipurpose wheeled vehicle. This mission option is the most constrained in terms of size and weight. Finally, the third mission option utilizes the system as part of the forward operating base’s (FOB) system of systems.
The criteria that were chosen from the output of the functional and physical architecture covered various aspects of the system. The system’s operational availability, reliability, and maintainability are of particular importance as they carry heavy implications for the operators and maintainers. The system’s power requirements as well as the portability are also key, as this system could be utilized in a forward deployed and isolated environment. Both life-cycle cost and life expectancy are significant from an acquisition and sustainment perspective. Finally, each system’s hydrogen-production rate is the chosen performance criteria as this value will drive further fueling and UAV sortie requirements.

The results of the MCDM model were indisputable—the LPE was the most preferred system option for every iteration of the model by at least 35%. This result was due to a few factors. First, the LPE is by far the cheapest option, costing almost half of the other two alternatives over the system’s life cycle. Second, the LPE is a much simpler system than either the ILPE or the AEOG, which historically results in longer operational availability, better reliability, and a more maintainable system. Finally, the LPE performs comparably to the highest performing alternative (the ILPE) and requires less power than the other alternatives. In terms of the mission options, the ship-based and FOB-based options are the most viable mission settings for the identified alternatives.

Although the LPE is slightly less than the threshold weight and size for mission option two, the proximity to the threshold results in an impractical solution. This presents a practical limitation of the effectiveness of the available systems to satisfy the mission options and limits the options available for the analysis of alternatives (AoA). Additionally, the TOPSIS methodology is only one option available to the decision-maker when executing MCDM models, so depending on the methodology used, the results could vary. Lastly, the classified nature of the ILPE precluded a thorough examination of the criteria, which could have presented some amount of error in the results of the AoA.

**Recommendations for Further Research**

This research could greatly benefit from future work. The Low Pressure Electrolyzer, Integrated Low Pressure Electrolyzer, and the Automatic Electrolytic Oxygen Generator are the only three systems that are qualified for use in the United States Navy. To integrate these systems in line with the mission options, modifications to the systems as well as the support elements (e.g., ships, base infrastructure, etc.) will have to be made to accommodate these systems. Future work including case studies of complex system modification as well as a determination of the viability of these systems from a ship system’s integration perspective would further validate this research.

Aside from the three systems identified in line with the sponsors’ qualification requirement, a closer look at the qualification process for a system of this caliber would be beneficial and could minimize the schedule and budget risk if or when new acquisition is executed, or an established system is repurposed to support a new mission. In addition to analyzing the procedure for qualification of a system such as an electrolyzer, an expansion of the alternative space could be advantageous.
We reviewed the model and implemented a number of improvements: (1) identified the cause of non-deterministic behavior and provided a resolution, (2) identified and fixed a logic error in the model that allowed serials to be counted as delivered though not traveling a path from source to destination for certain cases, (3) improved the rolling horizon implementation by more efficiently and effectively using decision variables, (4) modified the model to allow the use of alternative ports of debarkation (POD) and account for movement of serials from the POD to initial operational position (IOP), and (5) allowed the option to provide serials (loads) directly, bypassing the internal heuristic that maps individual pieces of equipment to serials. These changes were tested and implemented in a test file supplied with the final distribution.

We exercised the improved model over many variations to assess the impact of changes and compare two solution strategies (single iteration versus rolling horizon). We demonstrated that the improved model yielded a solution that delivered all serials in less time due to the more efficient use of decision variables. The single iteration solution strategy produced the solution with the lowest delivery time for the sample.
problem, but it also required more time to run. For both solution strategies, we demonstrated how effectiveness depends on key model parameters, and we recommend avenues for future research.

**Keywords:** logistics, delivery schedule, optimization, mixed integer program, design of experiments, expeditionary advanced base operations, EABO

**Background**

The Marine Corps requires tools to determine the optimal delivery schedule for a set of connectors to insert and sustain a distributed force executing the expeditionary advanced base operations (EABO) concept. Such tools should also be capable of evaluating how delivery time and schedule depend on the connector mix and other operationally-relevant parameters.

In 2019, Major Nicholas Freeman of the Combat Development and Integration OAD made significant progress towards this requirement by developing the S-MIP, an optimization model that produces an optimal delivery schedule for transporting an equipment set from designated source points to demand points, given the travel network, connector quantities, speed, sea state, carrying capacity, and ability to operate at each port (N. J. Freeman, PowerPoint Slides, May 1, 2020). Major Freeman implemented S-MIP using Pyomo, a Python-based optimization modeling language. The objective function minimizes a series of penalties that capture (1) total equipment reaching its final destination, (2) time to deliver equipment, and (3) distance to destination for any equipment that does not arrive at its final destination. In fiscal year 2020 (FY20), the researchers supported OAD by providing an initial review of the formulation and code and by developing the “connectorFarmer” and “connectorMiner” software to facilitate the execution and post-processing of experiments. This research was designed, in close collaboration with OAD, to extend the FY20 effort by providing a number of improvements to the S-MIP. These requested improvements provided the set of modeling research objectives.

First, initial experiments with S-MIP revealed that the model exhibited significant and unintended non-deterministic behavior, so the first research objective was to provide a detailed code review to identify and mitigate the cause of this behavior.

The second modeling research objective was to provide a detailed review of the implementation of the rolling horizon solution technique. When solving with a single iteration, the number of variables required, and thus computational time, can be so large as to be prohibitive. One strategy to address this issue is to break the problem into several smaller problems and to solve each one in succession. Each rolling horizon iteration solves one of these smaller problems in the overall multi-step solution process.

The third modeling research objective was to modify the S-MIP inputs file and code to (1) account for movement of serials from the port of debarkation (POD) to their initial operational position (IOP) and (2) allow for multiple/alternative PODs. A simplifying assumption was that travel time from the POD to IOP would be the same for all serials.

The fourth modeling research objective was to modify the S-MIP inputs file and code to implement an option to provide serials (loads) directly, bypassing the internal heuristic that maps individual pieces of equipment to serials. This allows for handling constraints not accounted for in the internal heuristic function.
The last research objective was to design, execute and analyze several experiments using the revised model to demonstrate the impact of model improvements and to assess the impact of varying the solution strategy as well as model and solver parameters.

Findings and Conclusions
We discovered that the undesired non-deterministic behavior was due to the use of Python sets to construct the inputs for the solver. By replacing these sets with lists and by switching to the use of a deterministic (instead of wall clock) time limit, the behavior was resolved. The review of the rolling horizon implementation fixed issues with how the code was handling serials from iteration to iteration, including initial positions and calculation of remaining distance. For example, in certain cases, it was possible for a serial to be marked as delivered and never handled again, though it did not travel a path from source to destination. Additionally, an error that allowed the model to use disallowed or nonsensical legs was identified and fixed. The code was also overhauled to streamline and reduce the problem size and to allow the size of the overlap parameter, which determines the extent to which previous decisions can be revisited, to change on each iteration, either upward or downward. This change requires more calculations than the previous downward-only movement implementation, but it makes full use of the number of variables on each iteration. The model’s inputs file and code were modified to (1) account for movement of serials from the POD to IOP, (2) allow for alternative PODs, and (3) allow the option for the user to provide serials (loads) directly, bypassing the internal heuristic that maps individual pieces of equipment to serials. These changes were tested and implemented in a test file supplied with the final distribution.

Several experiments were run using the improved model to examine the impact of model changes and to explore the impact of solution strategy (rolling horizon versus single iteration). The first experiment, to examine the impact of model changes using the original rolling horizon solution technique, compared the original model output to the improved model output, given a fixed set of inputs. The result demonstrated that the improved model yielded a solution that delivered all equipment in less time with the additional benefit of eliminating the need to run replications of the model. The improved solution was due to the more efficient use of decision variables, allowing for a greater number of previous decisions to be revisited with each iteration.

The next experiment varied the solution strategy and key model parameters such as the number of variables and size of the overlap. The S-MIP had not yet been evaluated using the single iteration strategy; therefore, the experimentation provided valuable insight on useful settings, such as how large the limit on the number of variables needs to be and how much time it takes to run. This experiment revealed that the single iteration solution strategy produced the solution with the lowest delivery time on a sample problem, but it did require longer run times. Overall, the main contribution was demonstrating the improvement in solution quality and run time possible via the tuning of parameter settings for a particular instance and solution technique.

Recommendations for Further Research
Five potential areas for useful research were identified. The first is to modify the model's internal heuristic that maps individual items of equipment to serials, the packages of equipment that the model moves around according to the decision variable settings.
For example, there is currently no incentive to keep equipment from the same unit together as much as possible, and this might constitute a useful variant for certain use cases.

Second, a simple heuristic might be developed to find a feasible solution with which to “warm start” the model. Starting with a feasible solution rather than “from scratch” might greatly reduce run time and allow a planner to find a good solution more quickly. The time savings could allow for a planner to re-run the model more frequently and account for input changes (i.e., a connector going down, temporary closure of a port, need to eliminate an arc due to oppositional activity along that route of travel, etc.).

Another possibility would be to reformulate the model to include parameters that capture operational risk. These parameters might include the probability of a detection or kill and number and type of escorts available to protect connectors. Taking risk explicitly into account would allow the planner to make choices based on both time to deliver supplies and likelihood of being targeted or incurring damage.

Additionally, the complementary use of optimization and simulation might be explored and demonstrated. The combination of simulation and optimization could provide a useful hybrid, flexible approach, since simulations are better at handling complexity, operational rules at a tactical level, randomness, and dynamic interactions over time. It might be useful to use the optimization model to generate a set of connector schedules relatively close in solution quality, then simulate those schedules to evaluate and down-select based on risk due to stochastic effects and/or oppositional actions.

Finally, using data farming, a larger design of experiments could be conducted that explore a wide variety of mix(es) of surface or air connectors needed to deliver equipment, personnel, and supplies to insert and subsequently sustain forces during conflict.

NPS-21-M238-A: Efficiently Using Families of Diverse Models to Better Inform Decision Makers in Objective and Repeatable Ways

Researchers: Dr. Thomas Lucas and Dr. Susan Sanchez
Student Participation: Capt Samuel Fitzmaurice USMC, Capt Sean Harper USMC, and Capt Caleb Kadrmas USMC

Project Summary
The United States Marine Corps seeks to integrate analytical processes that develop actionable insights for decision makers across its enterprise. One supporting goal in this endeavor is to develop a methodology for implementing a wargame-analytic continuum by formally linking outcomes of wargames with more traditional, constructive closed-form simulations.

The primary research objective was to explore methods and tools that provide the greatest utility when integrating wargames with constructive simulations, and this was accomplished via three main steps. The first step was to work with thesis students, each of whom studied a topic of current interest to the Marine Corps, assisting them with (1) the development of a constructive simulation scenario and (2) the design, execution, and analysis of one or more experiments.
The second step was to use the simulation-based effort to inform a wargaming activity. The third step was to conduct a literature review and produce a synthesis of findings and recommendations for future work.

The three student topics chosen were (1) anti-surface warfare battery lethality and survivability in expeditionary advanced base operations (EABO), (2) Marine infantry company lethality in a Force Design 2030 construct (Headquarters Marine Corps, 2020) and (3) cannon artillery lethality and survivability in a Russia counterbattery scenario. The first of these used the Modeling and Simulation Toolbox (MAST) simulation, and the latter two used the Map Aware Non-uniform Automata (MANA) simulation. Upon completion of their constructive simulation work, each used their data and insights to inform a sponsored wargame, under the auspices of the Operations Analysis (OA) 4604 Wargaming Applications Course.

A literature review was conducted and insights gained were synthesized with the students’ practical applications. Finally, a set of recommendations, best practices, and potential pitfalls for linking constructive simulation to wargames was developed. This work included capturing key concepts graphically through “loop of loops” and “sequence of iterations” diagrams.

**Keywords:** wargaming, constructive simulation, cycle of research, design of experiments, expeditionary advanced base operations, EABO

**Background**

As the Marine Corps focuses its efforts on implementation of Force Design 2030—a major change in organization, equipment, and concepts employment—it has an urgent need to analyze its tactics, techniques, and procedures (TTPs) with respect to employment of anti-surface warfare missile systems in EABO. At the same time, study is needed to determine how traditional Marine Corps capabilities need to adapt within this new context. Perhaps like no time in the recent past, the use of multiple modes of analysis and inquiry are crucial to studying and implementing such major change. Such modes include wargaming, constructive simulation, field experiments, and exercises. These modes can be implemented and integrated within a continuous “cycle of research,” a term coined by Peter Perla in his seminal book, *The Art of Wargaming* (1990).

The primary goal was to explore methods and tools that provide the greatest utility when integrating wargames with constructive simulations. By working with three thesis students, each with an identified topic of current interest to the Marine Corps, the study began by assisting each with the development of a constructive simulation scenario. Subsequently, each simulation scenario was methodically explored using one or more efficient and flexible experimental designs and high-performance computing assets. The output was studied using a variety of graphical and statistical methods.

The first student topic was anti-surface warfare battery lethality and survivability in EABO, and a base scenario was developed using the MAST simulation framework (Fitzmaurice, 2021). Designs of experiment varied several tactics and parameters related to battery lethality and survivability, for example, the use of an air defense missile system and active radar, concealment measures, anti-surface missile performance specifications, and timing of displacement.

The second student topic was Marine infantry company lethality in a Force Design 2030 construct, and a base scenario was developed using MANA (Harper, 2021).
Designs of experiment varied parameters and tactics related to the use of unmanned aerial vehicles (UAVs), sensor coverage, and the opposing force’s use of UAVs and naval surface fire support.

The third student topic was cannon artillery lethality and survivability in a Russia counterbattery scenario, and a base scenario was developed using MANA (Kadrmas, 2021). Designs of experiment varied parameters and tactics related to cannon artillery organization (consolidated versus levels of distributed operations), cannon performance specifications, and opposing force use of both cannon and multiple launch rocket system (MLRS) artillery assets.

Upon completion of the analysis, each of the students used the data and insights to inform a sponsored wargaming activity. Additionally, a literature review was conducted and insights gained were synthesized with the students’ practical applications. Finally, a set of recommendations for linking constructive simulation to wargames was developed.

**Findings and Conclusions**

Several interesting and important findings emerged from each student’s constructive simulation-based effort. The effort focused on the employment of anti-surface warfare missile systems within EABO produced the following main findings: (1) effectively engaging enemy ships from maximum effective missile range allows for both an increase of successful strikes against hostile ships and a decrease in friendly casualties; (2) selective and efficient use of friendly radar systems decreases the probability of being detected by enemy ships while still affording protection from enemy missile threats; and (3) remaining undetected by conducting survivability moves and use of overhead concealment dramatically increases survivability of friendly units ashore.

The effort focused on the Marine infantry company in a Force 2030 construct produced the following main findings: (1) engaging at maximum effective range is superior to mass surprised fires at the company level for this scenario; (2) victory is best generated by the force that first finds and employs sufficient loitering munitions on the other side; and (3) enabling a restricted operations zone where the future company commander owns airspace to a sufficient altitude and can self-clear all fires in his domain is critical to success.

The effort focused on the employment of cannon artillery in a Russian scenario produced the following main findings: (1) equipment currently fielded is largely in line with the most significant factors for lethality and survivability; (2) significant changes to current TTPs are necessary for force protection and mission success, namely adopting a more segmented and distributed employment of cannon artillery; and (3) inclusion of an MLRS capability by an adversary increases casualties for both sides and should be designated as a high-value target and prioritized for targeting.

Upon completion of the constructive simulation analysis, each of the students used the data and insights gained to inform a sponsored wargaming activity, under the auspices of the OA4604 wargaming applications course. Two of the students informed the Marine Littoral Regiment wargame sponsored by the Marine Corps Warfighting Laboratory, and the third student informed a Force Design 2040 wargame sponsored by the Australian Defence Force. The wargaming efforts were informed both qualitatively and quantitatively. For example, wargame performance specifications and player options were informed with information developed for or produced by a constructive simulation. Additionally, results from
constructive simulation-based analysis were used to shape wargame players’ available options, and in some cases, suggested how to adjudicate. Wargame results that corroborated similar findings from constructive simulation research were recorded, and qualitatively different results were discussed to probe possible causes and generate additional hypotheses.

Finally, insights gained from the literature review were synthesized with the students’ practical applications. We developed a set of recommendations, best practices, and potential pitfalls for linking constructive simulation to wargames. We also developed two diagrams, named “loop of loops” and “sequence of iterations,” to illustrate the key concepts graphically.

**Recommendations for Further Research**

Three potential areas for useful research were identified in this study of methods for integrating wargames with constructive simulations. The first is to gain familiarity with Command Professional Edition, a commercial wargaming and simulation environment in use by the Marine Corps Warfighting Laboratory and the Standard Wargame Integration and Facilitation Tool (SWIFT), a government-owned tool designed to allow games to be created, manipulated, recorded, and replicated in a digital environment.

The second area of future research is to investigate the extent to which Command Professional Edition and/or SWIFT might be used as the basis for post-wargame experimentation and analysis. Specific features of Command Professional Edition would be examined to determine the level of effort required to translate and automate human decision making within a data farming environment.

Finally, in consultation with the topic sponsor, a focused area of study would be selected and used as the basis to further develop the constructive simulation to wargame (or vice versa) link, given specifics of the problem and the simulation/software environments available to support the effort.

**References**


NPS-21-M006-B: Automated Cyber Operations Data Mission Replay

Researchers: Mr. Charles Prince, Dr. Gurminder Singh, and Dr. Alan Shaffer CDR USN Ret.
Student Participation: Capt Mark Petersen USMC

Project Summary
The research explored the capability of replaying cyber mission data (CMD) within the Persistent Cyber Training Environment (PCTE) infrastructure through the development of an application. The primary research question of how network specifications can be extracted from log data to create a digital twin network (DTN) of an operational network was answered by a proof-of-concept tool called the Automated Cyber Operations Mission Data Replay (ACOMDR), which can input intrusion detection system (IDS) Zeek CMD from the Big Data Platform-Cyber Hunt & Analytics Operation System (BDP-CHAOS) and produce a network specification to create a network similar to the original network (Petersen, 2021). A secondary research question, how can transformation of log data into executed scripts on a DTN be performed, was answered by the method ACOMDR working with Puppet. The ACOMDR to Puppet interface and application protocol interface (API), which have yet to be created, will be used to replay events, to control nodes, as well as interface with the PCTE automation tool. A completed working system will also require additional Puppet functionality to control the nodes. Another secondary research question, investigating desirable runtime environment features to control execution of cyber mission scripts, must still be determined.

Recommendations:
• Complete the development of a working prototype by completing the ACOMDR to Puppet interface and API to replay events, and to better extract network specifications from Zeek data.
• To create a higher fidelity digital twin network, refining the collection process that creates the Zeek data would also help by capturing more usable network data.
• To create networks faster, one should be able to use ready-made networks, and to correlate incoming Zeek data to best fit a set of ready-made networks.
• Investigate incorporation into PCTE a much higher fidelity virtualization system like Xen/Drakvuf, a malware investigation tool.

Keywords: digital twins, virtualization, cyber, security, cybersecurity

Background
The purpose of the study was to develop the capability of replaying CMD within the PCTE infrastructure through the development of an application. It requires creation of a virtual digital twin network based on network classification data. The Zeek classification data was accessed through BDP-CHAOS/PCTE and then used to create a raw database. In the database, unique datatypes were classified and placed in another database to be used in the creation of the virtualized digital twin network. The Zeek data was not rich in terms of classifiable information, and it is possible that some valuable data was filtered or purposefully left out. Filtering out data makes sense in that the data may have come from a classified network.
Joint Cyberspace Operations Forces should benefit from this study as this proof-of-concept tool may lead to timesaving automation of creating scenarios based on real world operational networks. By saving time in the creation of scenarios, the cycle from incident to training can be shortened, and PCTE is envisioned to be used by all commands.

Findings and Conclusions
We found that network specifications can be generated from IDS BDP-Chaos Zeek data, and a proof-of-concept tool was created to perform this task. We believe that a working system can be created to ingest IDS Zeek logs and use the data to create a representative network and control nodes on that network to simulate IDS incidents, but a working prototype for the system has yet to be created. During COVID, it took an extended period to locate the correct personnel and then to acquire the Zeek data and engineering documents, which adversely affected the number of items performed through completion.

We believe that this research effort should be continued to develop a working prototype of ACOMDR. Completing the ACOMDR to Puppet interface and API to replay events and to control nodes, as well as interface with the PCTE automation tool, are essential to completing the additional Puppet functionality to control the network nodes for attack replay. Additionally, the ability to search the BDP-CHAOS databases will result in increased functionality for the ACOMDR application. Creation of a graphical user interface to display views of digital twin network topology and cyber events over time on the digital twin network would enhance system capability. More work on inferring original network specifications based on Zeek data and translating it to the YAML specification needs to be performed. To support this, improving the Zeek data from the IDS may help the overall project greatly.

We also believe that adding ready-made networks to PCTE and then finding the best representative network according to incoming IDS Zeek data would be a valuable timesaving effort for PCTE. In addition, we believe that a study to add a Xen/Drakvuf high-fidelity virtualized network would be highly valuable to the study of malware for PCTE.

Recommendations for Further Research
Completion of the development of a working prototype by completing the Automated Cyber Operations Mission Data Replay (ACOMDR) to Puppet interface and application protocol interface (API) to replay events and control nodes would require additional work to develop the interface and API. Additional work on refining the extraction of network specification from the existing Zeek data to gather better network specifications to refine the process needs to be performed. This project would complete the existing study.

To investigate creating ready-made networks, one must modify the ACOMDR to be able to use this new feature and test the concept of correlating and analyzing algorithms used on incoming Zeek data to best fit ready-made networks. The hypothesis of this project would be that by using ready-made networks, a lot of time could be saved by end users that would not have to wait for a network to be created.

One can also investigate generating higher fidelity Zeek data by creating a better intrusion detection system/Big Data Platform-Cyber Hunt & Analytics Operation System such that the Zeek data can be extracted to make higher fidelity digital twin network specifications.
This process of intrusion detection system extraction would have to be looked at and analyzed. This project’s hypothesis is that a higher fidelity digital twin network could be created.

An investigation of the incorporation into Persistent Cyber Training Environment (PCTE) of a much higher fidelity virtualization system (HFVS) like Xen/Drakvuf would involve looking into PCTE to see what functions could be connected into an HFVS and may require development of infrastructure to support the connection. There may be additional functionality that must be created in PCTE and in the HFVS, as well as adaptation of ACOMDR into HFVS. The hypothesis for this project is that a network could be created that could test and develop malware that is aware of virtualization.

References

**NPS-21-M072-A: 5G for Field Expedient C2 Centers**

**Researchers:** Dr. John Roth, Dr. Frank Kragh, and Ms. Donna Miller  
**Student Participation:** Capt Jonathan Monti USMC

**Project Summary**
Integrating wireless communications technologies, specifically fifth generation cellular – new radio (5G NR), into military operations is a vital step in improving network capability, data sharing, and mobility for forward operating units. Current 5G methodologies include persistent, random direction, radio base station emissions to establish connections with mobile users. Combat risks associated with wireless emissions detection make such persistent, random direction emissions unacceptable for use in hostile environments. The power, random direction, and continuous nature of initial access transmissions from the base station greatly increases the likelihood of detection and interception of wireless communications. This research used computer validations to design a novel connection strategy based on mobile user connection initiation. This new connection strategy maintains the functionality of 5G networks while greatly reducing stray, high-power emissions from base station units thereby increasing the utility of 5G for operational military units. By initiating connections from the mobile user, a lower energy signal can be used to communicate with the base station, which in turn can extract direction-of-arrival information from the signal to return a directionally-focused signal, dramatically reducing stray emissions and total signal energy compared to the default 5G connection initiation method. Additionally, the base station can use specific shared information in this setup process to authenticate the mobile and prevent the base station from returning a signal to a non-friendly device. The research, and specifically, the computer validations show that the initial network access process proposed is much more suitable to the tactical military environment than the default 5G initial network access process. Further research to implement this methodology and test its suitability in a physical 5G NR testbed is recommended.
Keywords: 5G NR, fifth generation cellular - new radio, antenna arrays, beamforming, cellular telephony, EMCON, emissions control, mobile telephony, radio communications, tactical operations centers, wireless communications

Background
A primary initiative within the current strategic direction for the Marine Corps is to increase the mobility of tactical command centers thereby reducing their vulnerability to attack. The need for low probability of detection (LPD) communications is included because adversaries will hunt for and target conventional radio transmitters. This research addresses the issues of mobility and LPD by proposing a novel connection method that would allow commercial fifth generation cellular – new radio (5G NR) technology to be incorporated into the Marine Corps’ (and larger military’s) command, control, communication, computers, and intelligence (C4I) infrastructure while addressing these issues.

The United States military has long been caught between the need and desire to incorporate wireless technologies into its C4I infrastructure and the requirement to maintain secure communications. Two major areas of concern in implementing wireless technologies are the security of the communications, that is, the certainty that enemies cannot intercept our information relayed over wireless channels and the risks associated with the detection of wireless communications. Even if the information being transferred cannot be deciphered, detection alone can be catastrophic for a military unit as key information such as unit activity or geolocation data can be ascertained by detecting radio signals.

Wireless technologies, by their nature, provide for increased mobility for the connected user or device. However, it is not simply the mobility of the user or device that is increased, it is the mobility of the system as well. A wireless system can be moved from location to location and either maintain or resume network operations orders of magnitude faster than its wired counterparts. Wireless communications is a necessary component of increased unit mobility.

Wireless technology also provides a level of network flexibility not found in wired systems. Adjusting architecture, opening and closing connections, and expanding or contracting network size can all occur much faster and with less manpower in a wireless network as compared to wired systems.

5G NR offers many benefits over previous wireless technologies, most notably in the area of increased data rates, reaching throughput over one gigabit per second (Gbps) (Al-Falahy, 2017), and physical layer security improvements over previous wireless technologies by taking a more holistic approach to security and implementing it at all levels within the system. Lastly, and most important to this research, is the implementation of massive multiple-input multiple-output (MIMO) technology in 5G NR which allows a system to focus radio energy in space (Ghosh, 2019). The latter attribute is vital to endeavors involving LPD communications and is why 5G NR was chosen as the focus of this research.

In this work, the default 5G NR network access initiation process was scrutinized with the goal to reduce radio emissions as much as possible with the minimum necessary changes to the default process. A modified process, user-side equipment connection process (UECP), was designed in this research. Computer validation was used to verify that UECP enables network access initiation with substantially less radio vulnerabilities than the default 5G NR network access initiation process.
Findings and Conclusions
This research offers a UECP as a potential new method for 5G NR radio devices to connect in operational military environments where radio emissions represent risk. This process maintains 5G NR functionality. UECP eliminates the requirement for the transmission of periodic broadcast signals to search for mobile users within the coverage area and enables initial network access while using much less signal energy than the default 5G NR initial access procedures.

The important distinctions between the UECP designed in this research from the default 5G NR initial access procedure include (1) the mobile user equipment initiates the access request and not the base station, (2) the base station uses the mobile user’s initial request to estimate the direction to the mobile user, and (3) the base station replies to the mobile user using a highly directional low energy signal. Although the mobile user’s antenna does not permit a directional transmission, the large gain of the base station’s antenna, coupled with the phased array sweep listening (PASL) process designed in this research, permits the initial access request to be sent from the mobile user with minimal signal energy. The PASL process uses various steering vectors to phase-correct the incident signal across all base station antenna elements before correlating them against the known preamble signal value, enabling detection with low signal to noise ratio (SNR). The research quantifies the required received SNR as a function of base station antenna array size.

This research also compared the PASL process to the commonly-used MUSIC algorithm for estimating the signal’s direction of arrival. It was shown that PASL determines accurate direction of arrival with less signal energy than required by MUSIC. The direction of arrival estimated by the PASL process can also be used to phase-correct the payload signals received before demodulation, which greatly decreases the bit error rate, increasing the probability of successful initial network access.

Throughout this research, it was shown that all the processes and methods used would benefit from the creation and utilization of large antenna arrays at the base station, an important aspect of 5G NR technology. As array sizes, frequencies used, and computational power of systems increase, as is expected, the methods proposed in this research become more effective in initial access of 5G NR-based systems in environments where radio transmissions need to be tightly controlled.

Recommendations for Further Research
The attack model in this research assumed hostile transceivers have the ability to craft and send a connection request. However, it also assumed these hostile transceivers do not have the ability to jam signals or continually transmit in a denial-of-service type attack. These are important considerations for the battlefield environment and a risk analysis should be conducted.

The phased array sweep listening (PASL) method proposed in this research is very effective in facilitating the connection of two radio devices while minimizing stray radio emissions. However, this method is highly computationally intensive in its current form. Because PASL must occur in real-time, this computational load is a concern. Although the currently proposed method works, further study into optimizing and increasing the efficiency of the process is warranted.

Signal time duration and antenna array length are two primary parameters in this work. Although it was shown that a trade space exists between these two variables, there also exists a lower bound where the
user-side equipment connection process (UECP) performance is difficult to predict. Additionally, as the signal length decreases, the array length must increase, but the exact performance of the system at ultra-high array lengths and ultra-low sequence lengths has not been fully explored. The PASL process is computationally intensive, and as either the sequence or array values get too large, the computational time required becomes prohibitive, and high-power computational platforms would be required to conduct the calculations. Further analysis at these extreme values using a high-power computer would be prudent to determine if the characterizations presented in this paper are valid in the more extreme cases.

In this work, we propose that timestamps are necessary, but a more definitive determination of the range of allowable values based on the connection request length is required. As the signal time duration and symbol length increase, the probability of a hostile transceiver being able to randomly create a signal that could fool a friendly receiver decreases. The longer the duration of the signal, the more time a hostile transceiver would require to try all possible signal values, but the greater the mobile user’s radio energy emitted during the connection request process. Decreasing signal duration decreases the time required for a hostile transceiver to craft a valid connection request through random signal creation and would, therefore, force a decrease in the range of acceptable timestamps. The practical application of UECP would require some knowledge or assumption of a hostile transceiver’s ability to craft a valid request through arbitrary connection request creation that could be used to determine the maximum allowable range for the timestamp.

References

HQMC INSTALLATIONS AND LOGISTICS (I&L)

NPS-21-M159-A: An Analysis of Repairable Items Lead Times at USMC Wholesale ICP

Researchers: Dr. Geraldo Ferrer and Dr. Margaret Hauser
Student Participation: Capt Jason Frey USMC

Project Summary
The Wholesale Secondary Items Inventory Manager of the Marine Corps Logistics Command (MARCORLOGCOM) is tasked with providing secondary repairable (SECREP) materiel to its customers to enable mission accomplishment. The enterprise wide SECREP inventory totals nearly 250,000 items valued at approximately $900M, and the SECREP inventory at the wholesale level is the last line of defense for ensuring the Fleet Marine Force has the materiel needed for continued and sustained operations.
The wholesale SECREP inventory levels are maintained through the execution of procurement and repair actions totaling $30M/year and $50M/year, respectively, through six different attainment channels. Each channel consists of three different subsegments that make up the total lead time associated with the replenishment actions. The lead times between a SECREP procurement or repair action and the time the materiel is available for use is an important performance metric affecting SECREP inventory levels and availability. This study focused on identifying which subsegments of lead time across the six wholesale attainment channels should be targeted with reduction efforts to decrease inventory levels while still providing the same level of mission support.

To understand how each subsegment lead time affects SECREP inventory, we created a model to emulate system behavior. Customer demand data and wholesale transactional data was analyzed for a few items stocked by MARCORLOGCOM to estimate the time spent with each attainment channel subsegment of the SECREP replenishment process.

Finally, we conducted a simulation experiment that varied the subsegment lead times in each attainment channel. The model showed how MARCORLOGCOM’s wholesale inventory level changed with the modified attainment channel subsegment lead times. The analysis indicated that the attainment channel subsegments that provide the greatest inventory reduction (by reducing their lead times) also provide greatest inventory value reduction while still providing the same level of customer service.

**Keywords:** secondary repairable materiel, inventory management, lead time reduction, procurement lead time

**Background**
MARCORLOGCOM’s wholesale inventory of SECREPs is continuously depleted as it meets customer demands, thus prompting the need to reorder materiel to replenish its stock. There are two acquisition methods to accomplish SECREP replenishment: procure new materiel or repair unserviceable materiel. There are two distinct procurement and four repair processes, or attainment channels, that MARCORLOGCOM can adopt to source the needed SECREPs for wholesale inventory replenishment, described below:

1. Inter-service procurement: purchasing SECREPs directly from other Department of Defense (DOD) service branches;
2. Defense Logistics Agency commercial procurement: purchasing SECREPs from commercial vendors;
4. Depot Maintenance Inter-Service Agreement repair: invokes a formal agreement between DOD branches to repair USMC SECREPs;
5. Commercial contract repair: employs a contracted commercial vendor to repair SECREP materiel;
6. Logistics integration support: enables the repair of SECREPs at pre-defined prices and repair durations.

The attainment channels’ lead times are known as either procurement lead time or repair cycle time, depending on the acquisition method, described below:
1. Procurement lead time can be broken down into three distinct subsegments:
   a) Pre-attainment lead time (P-ALT) subsegment, which begins when the requirement for a SECREP is identified, and it ends when a formal procurement requirement enters the inventory management system.
   b) Contract lead time (CLT) subsegment, which begins when a formal requirement enters the inventory management system. It ends when the procurement contract is awarded.
   c) The production lead time subsegment begins when the procurement contract is awarded, and it ends when the materiel is delivered.

2. The Repair Cycle Time consists of similar sequential subsegments. It is also composed of three subsegments:
   a) The P-ALT subsegment for the repair attainment channels, similar to the one in the procurement lead time.
   b) The CLT subsegment for repair attainment channels begins when a formal repair requirement enters the inventory management system, and it ends once it is processed.
   c) The source of repair cycle time begins when the owner of the selected repair attainment channel receives the unserviceable SECREP, and it ends when the repaired materiel is delivered.

This study analyzed attainment channel subsegment lead times from two different perspectives. First, we evaluated how attainment channel subsegment lead times affected the number of SECREPs MARCORLOGCOM needed to manage its inventory. Second, we identified how the inventory value correlated with the lead time in each attainment channel subsegment.

A continuous review inventory model was created to emulate the MARCORLOGCOM wholesale SECREP inventory and replenishment cycle. The model was subsequently subjected to a discrete event simulation, which helped understand how attainment channel subsegment lead times impact MARCORLOGCOM’s required investment in wholesale SECREP materiel. The analysis identified which subsegments should be targeted to obtain greatest reduction in wholesale SECREP inventory investment while maintaining the mandated service level.

Findings and Conclusions
The models showed that the same attainment channel subsegments have the greatest impact on inventory level and inventory value. MARCORLOGCOM should direct lead time reduction efforts at the mean lead time values of these attainment channel subsegments for wholesale SECREP inventory reduction.

The second conclusion was that both performance metrics were more sensitive to reductions in the lead time mean than to reductions in lead time variability. This is a surprising result given that variability in demand tends to have the most significant impact on inventory management performance metrics.

Recommendations for Further Research
The limitations of the Marine Corps Logistics Command’s (MARCORLOGCOM) inventory management system made the analysis of pre-attainment lead time (P-ALT) and contracts lead time (CLT) subsegments particularly difficult. P-ALT data was not available, requiring the authors to estimate the subsegment’s lead time distribution. Additionally, the information about the CLT subsegment that could be extracted from the historical transactional data seemed to imply that MARCORLOGCOM’s business
rules, internal processes, or data collection requirements changed within the past few years, making it difficult to obtain consistent results. For these reasons, it is recommended that a deeper analysis of P-ALT and CLT be performed with newer data to gain a better understanding of the lead time distributions and to obtain more accurate results.

HQMC MANPOWER AND RESERVE AFFAIRS (M&RA)

NPS-21-M035-A: Understanding Motivational Factors of Problematic Video Gaming in the USMC and USN

Researchers: Dr. Panagiotis Matsangas, Dr. Nita Shattuck, Dr. Lawrence Shattuck, and Dr. Darian Lawrence-Sidebottom

Student Participation: LT Jason Xu USN and ENS Edrie Orpilla USN

Project Summary
The overarching aim of the project was to assess attributes and aspects of video gaming in the Marine Corps and U.S. Navy. Survey data were collected from three U.S. Navy surface ships (two in port, one deployed) and three United States Marine Corps commands. Marines also participated in semi-structured focus groups. Response rates to the surveys ranged from ~7.5% for Marines to ~22.5% for Sailors. Respondents consisted of 68 Sailors and 927 Marines (median age of 24 years, 92.4% males, 84.2% enlisted). From these 1,013 active-duty service members (ADSMs), 91.6% reported playing video games (VGs) (median age of 23 years, 94.3% males, 86.1% enlisted). Results suggest that video gaming is highly prevalent in the military. Video gaming occurred more frequently at home/off duty than when on duty or when underway/deployed. Self-identified gamers reported video gaming later in the day and, depending on the setting (at home/off duty, on duty, underway/ deployed), 5 to 18% of gamers reported sleeping later due to gaming. Self-identified gamers reported symptoms of depression (~23% of ADSMs), generalized anxiety disorder (~19%), and excessive daytime sleepiness (EDS) (~33%). Approximately 39% of these gamers had Alcohol Use Disorders Identification Test (AUDIT-C) scores suggestive of heavy drinking and ~32% reported dissatisfaction with their life. More excessive gamers tended to be younger, use dysfunctional coping styles more frequently, and play video games more frequently and for more hours. Also, more excessive gamers were more likely to have symptoms of major depression, generalized anxiety, and EDS, and they were also more likely to report sleeping later because they played VGs. Depending on the criterion used, the prevalence of disordered gaming in the study samples ranged from 0 to 4.85%. Of those who reported playing VGs, ~50% of Marines and 25% of Sailors were identified as problematic gamers. We developed several recommendations and action items to include follow-on research.

Keywords: problematic video gaming, video game, addictive behaviors, psychological functioning

Background
Video gaming is a popular activity among ADSMs. The prevalence is not unexpected given the relatively young age of many ADSMs and the high prevalence of video gaming in the United States population.
Video gaming has been associated with cognitive benefits, including improvements in visual selective attention (Green & Bavelier, 2003), speed of processing (Dye et al., 2009), and executive functions (e.g., decision making and problem solving) (Buelow et al., 2015). Video gaming may also be a tool for coping with stress. This benefit may be especially important in military operational settings which are characterized by high levels of occupational stress and poor sleep conditions, which increase the risk of depression, anxiety, and sleep disorders.

In contrast to normal gaming, excessive video gaming may result in degraded well-being and health outcomes. Studies have shown that excessive video gaming is related to high stress levels (Milani et al., 2018), lower psychosocial well-being and psychological functioning (von der Heiden et al., 2019), loneliness and depression (Lemmens et al., 2011), and delinquency and aggressive behavior (Engelhardt et al., 2011; Ewoldsen et al., 2012; Milani et al., 2018). Video gaming may also be related to poor sleep, especially when gamers stay up late playing video games (Matsangas et al., 2020). In extreme cases, video gaming can become an addiction. In the scientific literature, Internet Gaming Disorder (IGD) is associated with poor emotion regulation, impaired prefrontal cortex functioning and cognitive control, poor working memory and decision-making capabilities, and neuronal deficiencies characteristic of substance-related addictions (Kuss et al., 2018).

The overall aim of this project was to assess attributes and aspects of video gaming in the United States Marine Corps (USMC) and United States Navy (USN). The specific objectives were the following:

1. Assess the prevalence of video gaming.
2. Assess the prevalence of problematic video gaming and/or addiction to video gaming.
3. Explore why Marines and Sailors engage in video gaming.
4. Explore whether Marines and Sailors are using gaming as a maladaptive coping mechanism.
5. Identify the key intrinsic factors (e.g., demographic characteristics) and extrinsic factors (e.g., occupational or other) associated with video gaming.
6. Assess the effect of video gaming on Marines’ and Sailors’ behavior, quality of life, and everyday functioning.
7. Provide recommendations focused on existing Marine Corps Community Services programs and Sailors to promote healthy coping behaviors in response to stressors.

The study included two major components: Navy and Marine Corps. The first component (Navy) collected data from Sailors on three United States Navy surface ships (two in port, one deployed). Sailors filled out a paper-based cross-sectional survey. Deployed Sailors completed a daily paper-based activity log for 10 days while Sailors who were in port filled out the activity log online. The second component (Marine Corps) collected data from Marines in three commands that were selected by the Marine Corps Headquarters. Marine participants took the cross-sectional survey online; a subset from the three commands participated in semi-structured focus groups.

**Findings and Conclusions**

Consistent with studies in civilian populations, our results suggest that video gaming is highly prevalent in the military. Compared to the limited number of non-gamers who participated in our study, self-identified gamers were more likely to be young, enlisted males. Many gamers reported that video gaming began early in life, around 7 or 8 years of age.
In terms of coping styles, both Marines and Sailors who played video games used problem-focused and emotion-focused coping styles more frequently than dysfunctional coping styles. The most frequently reported motivation for video gaming was recreation, followed by coping with stress. In general, more respondents reported video gaming at home/off duty than when on duty or when underway/deployed. Sailors, however, seem to be more consistent than Marines in their video gaming habits. Depending on the setting (at home/off duty, on duty, when deployed/underway), gamers reported playing video games on average 3.75 to 6 days in a typical week for approximately 2 to 3 hours/day. The most frequently reported devices used for video gaming were game consoles and smartphones. In general, gamers reported video gaming later in the day (i.e., after work and before bedtime) and, depending on the setting (at home/off duty, on duty, underway/deployed), 5% to 18% of gamers slept later due to video gaming. Most gamers reported video gaming in their racks or the mess decks/common areas when deployed/underway. In both USN and USMC populations, self-identified gamers reported symptoms of depression (~23% of the ADSMs) and generalized anxiety disorder (~19%). They also exhibited excessive daytime sleepiness (~33%), AUDIT-C scores suggestive of heavy drinking (39%), and ~32% of gamers reported dissatisfaction with their life. Finally, excessive gamers tended to be younger, to use dysfunctional coping styles more frequently, and to spend more time in video gaming activities (i.e., gaming more frequently and for more hours). Excessive gamers were more likely to report symptoms of major depression, generalized anxiety, and excessive daytime sleepiness, and were also more likely to report sleeping later due to video gaming.

We devised a classification scheme that considered video gaming as a continuum with three mutually exclusive groups (normal, problematic, and disordered gamers). The “disordered” classification was based on three factors (psychological status and health, styles of coping with stress, and time management expressed by whether video gaming interfered with their sleep). The “problematic” classification was based solely on the time management factor and assumes that gamers do not have any issues related to their psychological status/health and styles of coping with stress. The application of the three-group model led to the conclusion that approximately 50% of Marines and 25% of Sailors who reported playing video games in our sample could be identified as problematic video gamers. Also, depending on the validated criterion used in civilian populations, the prevalence of disordered gamers in the study samples ranged from 0 to 2.20%. With the revised criteria we developed, the estimated prevalence of disordered gamers ranged between 1.3% and 4.85%.

**Recommendations for Further Research**

Based on our findings we developed several recommendations and action items.

1. Develop video gaming training for leadership and active-duty service members (ADSMs). Specifically, ADSMs should be educated about the negative effects of video gaming to include video games’ (VGs) roles as “time wasters” and “sleep thieves,” and the potential risk of addiction.

2. Conduct a sleep study using objective methods to reliably assess sleep/wake patterns and sleep attributes of gamers (e.g., sleep duration, timing, quality).

3. Conduct a follow-on study to validate the current findings and to assess the prevalence of video gaming more reliably in the United States Navy and Marine Corps. This study would add a few questions related to video gaming to a more general survey that is not focused on video gaming per se (e.g., the Navy’s command climate surveys).
4. Even though tools like the Internet Gaming Disorder Scale–Short-Form (Severo et al., 2020) are extensively validated in civilian populations, existing criteria are not tailored for military personnel or the unique demands of military operational settings. The criteria for “problematic” and “disordered” video gaming need to be refined and tailored for the military.

5. Assess whether and how video gaming behaviors change after joining the military.

6. Assess the effect of other “time wasters,” such as time on the internet and social media use. Even though technology use is often a means of relaxing from the stress of military life, the overuse of technologies can perpetuate sleep disturbances by increasing arousal right before bedtime (Troxel et al., 2015).

References


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Researchers: Dr. Anne Marie Baylouny, Dr. Susan K. Aros, Dr. Mollie McGuire, and Mr. Chris Keptonglard

Student Participation: No students participated in this research project.

Project Summary
This project investigated the psychological, physiological, and social effects of the use of flashbang grenades (FBG) for less-lethal crowd control and other intermediate force purposes. Our objective was to determine the specific elements that make FBGs effective, when they are less effective, and to develop a conceptual FBG effects model that includes such effects. The conceptual model would then feed our computer simulation model under development, called Workbench for refining Rules of Engagement against Crowd Hostiles (WRENCH). We examined the psychological dynamics of FBGs, reviewed documented physiological literature, extrapolated social psychology effects, and examined case studies of use in crowds including videos. We concluded that more research on case studies of FBG use in crowds is needed. The physiological and experimental data on effects is inconclusive and limited to individuals, without considering group dynamics, context, experience, expectations and perspectives of security forces. All these factors are necessary to adequately predict or model a crowd’s behavior.

Keywords: crowds, non-lethal weapons, flashbang grenades, FBG, social identity, less-lethal weapons, intermediate capabilities, stress, stun weapons, non-lethal weapons, WRENCH, Workbench for refining Rules of Engagement against Crowd Hostiles, simulation, social identity

Background
Under Joint Intermediate Force Capabilities Office (JIFCO) funding, the Naval Postgraduate School has developed the WRENCH Simulator: a complex agent-based simulation modeling environment that enables commanders to explore the effects of different non-lethal-weapon rules-of-engagement for encounters with non-combatant crowds in different scenarios. WRENCH incorporates social modeling, identity dynamics, and needs modeling into an operational scenario where security forces interact with populations to manage the operational scenario. The primary objective of this project is to investigate the psychological, physiological, and social effects of the use of flashbang grenades (FBG) for less-lethal crowd control and other less-lethal purposes and to develop a conceptual FBG effects model that includes such effects.

FBG has not been studied with identity and social variables. Such variables can alter the reactions of individuals and crowds, including past and present experiences of deprivation, amount and type of social organization, evaluations of risk and existing levels of tolerance for violence and shock, for example.
These differences need to be researched and understood to advise on the circumstances in which FBG should be used to achieve the intended result, either crowd dispersal or a decline in adversarial actions against security forces.

The cognitive and psychological effects on behavior of FBG are crucial in recommending their use, which is central to the sponsor’s mission, since less-lethal weapons are intended to alter behavior. Crowds are diverse in their composition, quite possibly resulting in different responses to a variety of less-lethal weapons, particularly FBG.

Studying the social variables in the use of less-lethal weapons is necessarily complex. To date, the numerous experiments examining stun weapons and the stress effects that follow have focused on the individual and his/her reaction to an FBG. Experiments have not considered the effects, from short- to long-term, of the use of these weapons on the smaller groups that make up crowds. The effects on social identities over the long term have not been analyzed, for example the effect on memory and future use. Do groups become accustomed to the use of FBGs and, therefore, these weapons lose their effectiveness? Do the weapons agitate more than disperse a crowd through their effects on people nearby the individual targeted?

For this study, we examined extant literature on the human response to FBGs, the social identity literature for reactions to such weapons, and analyzed a broad sample of footage from crowds subjected to FBGs. This provided us with the mechanism and theorized physiological effects and human reactions from psychology, sociology, and case studies around the world.

Findings and Conclusions
We sought to determine if FBG use translated into dispersal of the crowd or, at a minimum, a decrease in adversarial behavior. Our results confirm stress findings of physiological effects but question the translation of those effects into human actions that are effective for crowd control under all circumstances. Possible reactions include flight, fight, or freeze. Stress can cause all of these in an individual. Experiments have shown that FBGs stun individuals for less than a minute, and this distraction is the objective of FBG use in criminal or military usage, allowing security force personnel to enter without adversarial action. The perception of FBGs as an effective less-lethal weapon has translated into their heavy use in crowd control scenarios.

The physiological and social psychology literatures both yield uncertain conclusions regarding context and memory for the use of FBGs. Stress responses vary among individuals due to experience, expectations, and evaluation of threat, among other variables. Intensity of belief in the reason for confronting security forces and perceptions of illegitimacy also affect responses to the use of FBGs. These questions are exacerbated in crowd situations where people look to others to determine their own actions and participants in the protest have a variety of experience with such weapons. The result will also vary by the laws of a country and the expectations of protesters. In countries where lethal force is often used, FBGs can be interpreted as live ammunition, causing the crowd to flee. Where security forces operate along rules of minimum harm to civilians, video evidence has shown protesters were far less affected by FBGs.
Our conclusions question the use of FBGs in democratic contexts with civil rights while demonstrating tentative evidence supporting the use of other less-lethal weapons. Data from social identity literature on disasters indicates the dominance of helping behavior among victims, not panic or self-serving behavior. We see these effects in video case evidence of FBG use. A wide variety of behavior was evident in these cases, from individuals remaining unaffected despite numerous FBGs in the vicinity, to immediate flight in non-democratic contexts, to throwing weapons back at security forces. Youth and young males appear most unaffected and adversarial after the use of FBGs in these protests.

These conclusions mean we need to break down the diverse elements of context and social identity to model the effects of FBGs in crowds. The model would need to break down crowd types by context and participants, for example historical perceptions of legitimacy of security forces, expectations and memory of behavior, degree and strength of social identity unity among the crowd, and the salience of the issue for the crowd.

With these findings the sponsor can request further research specifically into crowds and the use of FBGs and compare that to other less-lethal weapons used with crowds. Videos and case studies of crowd events compared across contexts and issues would be particularly useful in delineating when FBGs would be effective, ineffective, or backfire into escalation.

**Recommendations for Further Research**

We recommend continuing to explore the video evidence of flashbang grenade (FBG) use in crowds and documenting how each crowd response varies by history/experience, expectations and law, and social identities. We see the effect of FBGs in crowd scenarios varied by social psychological elements including country and dominant laws (expectations), experience of the protesters, and context of the protest. Perception and purpose were key, as were the actions of smaller groups making up the crowd.

Our initial look into this data source verified many of our hypotheses regarding the use of FBG which run counter to their purpose in crowd use. Real-life demonstrations of how FBGs affect actions, the second dynamic after the initial physiological effect that is non-voluntary, can yield more answers that experiments cannot. Experiments are generally focused on the individual effects while what we found was that social relationship, beliefs, purpose, and memory, all components of social identity, crucially alter the response to such stun weapons.
NPS-21-M319-A: Cognitive Assistance with AI COAs: Radical Rethinking of HMT Mission Workflows and Decision Making as AI Assumes a Peer Relationship with Operators

Researchers: Ms. Sharon Runde, Dr. Curt Blais, and Mr. Arkady Godin

Student Participation: No students participated in this research project.

Project Summary
This study researched the factors of situational awareness (SA) as they relate to decision quality in tactical decision making. This is an ongoing issue for the Marine Corps Headquarters (MCHQ), Plans, Policy, and Operations (PP&O) with lethal consequences. First, the stages of the evolution of human-machine teaming (HMT) mission workflows were assessed. Stages focused on transitioning automation tasks from humans to machines. Study began within the context of interdependency analysis (IA), a technique which is used as part of a co-active design in the process of digitization of mission workflows such as fire support coordination (FSCn). We also studied the evolution of HMT to include various tools used to determine courses of action (COAs) for decision making with artificial intelligence (AI) and what role natural language processing (NLP) plays. In addition, this study explored the viability of an IA matrix and NLP in HMT peer-to-peer COAs generation paradigm as opposed to other approaches.

The main research questions included 1) What is the best approach for a cognitive assistant (CA) to learn mission workflows? 2) How can a CA switch between modes of automatic, advisory, or monitoring? and 3) What are the conceptual considerations that must be understood to make decisions, as well as the ability to switch contexts?

This research resulted in a comprehensive literature review covering topics in AI, command and control, cognition, cyber, decision-making, decision support systems, fire support coordination, HMT, human systems integration, knowledge management, naturalistic decision making, situational awareness, and wargaming. Upon reviewing the literatures, a more nuanced and detailed phenomena emerged. The top-level issue may be a lack of SA. However, the causes of decreased SA can be reduced to factors of noise such as environmental, physical, or technological. A deeper investigation identified a potential dependent variable of “ignorance” with an independent variable of decision quality.

Keywords: human-machine teaming, HMT, automation, artificial intelligence, AI, courses of action, COAs, decision making, decision support systems, fire support coordination, situational awareness, SA, cognition

Background
This research studied a conceptual framework for a novel decision support system that centralizes the user in the system. A cognitive assistant (CA) is a combination of hardware and software that augments human intelligence (Engelbart, 1962, 1995). A CA does not replace the human decision-maker; rather, a CA enhances human capabilities. The idea of augmenting human intelligence has been researched dating back to the 1940s (Dreyfus & Dreyfus, 1986).
Key aspects of this new conceptual framework will focus not only on human decision making, but computer-aided decision making. The novel contribution of this work is that a CA would gather information, learn SA and share COAs with humans while allowing multiple modes of operation of the system, namely, the ability to monitor, provide advice, or have full autonomy within parameters. The system will utilize AI and machine learning (ML) algorithms to process information from multiple data sources. The CA represents the system framework that can automate tasks to improve FSCn and corresponding SA. To illustrate the CA, this research focused on the MCHQ PP&O Fire Support Coordination Center (FSCC) planning at the tactical decision-making level. Beyond this first conceptual framework, the theory-testing and development and proposed solution should be generalizable to higher levels such as operational and strategic planning.

The goal of this research extended the design principles for intelligent CAs so that human decision-makers are equipped with decision support tools that provide a tactical edge in command-and-control situations. A CA that can learn SA and provide COAs would result in lower cognitive load of FSCn unit personnel, improve speed and quality of decision making, decrease decision-making errors, and ultimately, reduce fratricide, unintended civilian casualties and/or excessive physical destruction.

This study took a comprehensive review of multiple literatures including AI, command and control, cognition, cyber, decision making, decision support systems, fire support coordination, HMT, human systems integration, knowledge management, naturalistic decision making, NLP, SA, and wargaming.

The original hypothesis stated that a CA could improve SA for FSCn personnel. A visit to 29 Palms, California provided an opportunity to observe the training exercises for FSCn personnel. Data was collected by attending the pre-brief meetings to understand the scenarios, determining who was responsible for different types of decisions, and observing the exercise unfold. To ensure reliability of the data collected, photographs were taken, and audio recordings were obtained so that any observational notes taken could be compared to the actual events. The data collected was organized and sorted for a high-level analysis to find themes and patterns. The themes and patterns were then distilled into factors that affect SA, such as environmental, physical, and technological. These key factors drove a deeper investigation into understanding types of decision errors, styles of decision-making, and other cognitive factors. These areas were studied to extend our understanding of cognitive load and situational awareness to apply it towards a CA.

Findings and Conclusions
Upon reviewing the literatures, a more nuanced and detailed phenomena emerged. The top-level issue may be a lack of SA. However, the causes of decreased SA can be reduced to factors of noise such as environmental, physical, or technological. A deeper investigation identified a potential dependent variable of “ignorance” with an independent variable of decision quality. The key issue of SA is not knowing what one does not know and not knowing to ask for new or different information. This is where a CA can parse through large volumes of data from multiple sensors and sources to “make sense” of the environment and push additional insights to the operators, thus augmenting the operators’ SA to ask questions they do not know how to ask or formulate.

The research questions evolved to consider: Where do errors enter and propagate? What is the effect of decision errors on the mission and lives?
With a CA, it is hypothesized SA would improve, but a new question arose: with conceivably more or “better” information, at what point would decision quality decrease regardless of SA due to a limit of cognitive load on humans? Higher levels of SA may improve decision quality to a certain point, but more may not always be better. Rasmussen (1986), as cited in Hutchins (1996), argued that human processing capabilities have “remained almost static for thousands of years.” So, even with perfect SA, human processing capabilities reach a peak limit, and beyond that peak are diminishing returns. Once a decision maker reaches peak saturation of SA, more information will only contribute to higher cognitive load. It is at this nexus of SA and decision quality that a CA can provide the tactical edge for our military to outperform our enemies.

The challenge is the breadth and depth of the problem. This research will attempt to select the best-of-the-best and synthesize the components into a general framework that can be broadly applied to any complex, dynamic, and critical decision-making environment. In doing so, other conclusions drawn from the literature reviews revealed that NLP may be a viable approach to designing a CA, but it is not sufficient as a theoretical application. As such, this resulted in additional theoretical frameworks studied and identified to situate the research appropriate for military applications. Two theories identified were General Systems Theory (GST) and Naturalistic Decision Making (NDM) Theory. GST provides a framework for measuring/testing key elements such as feedback in an open, complex system. NDM Theory is concerned with “how people make decisions in complex real-world settings that can include dynamic, uncertain, and continually changing conditions, and can require real-time decisions in urgent situations with significant consequences for mistakes” (Naturalistic Decision Making, n.d.).

The potential impact of creating this framework would change the rules for the U.S. to have a system providing a competitive advantage against hostile nations and intrinsically provide information dominance in the battlefield.

**Recommendations for Further Research**

Further research on this study will address and support the current Force Design 2030 challenges in alignment with the strategic guidance from The National Defense Strategy. This includes completing this research towards “iterative wargaming, analysis, and experimentation” (Corps, H. M., 2020). Utilizing an expeditionary advanced base operations scenario and collaborating with the Joint Artificial Intelligence Community, the conceptual framework that will be developed from this research can be tested and analyzed. In addition, considering a general framework broadly applicable to rapid decision-making environments, the researchers plan to have discussions with Dr. David Ferrucci, creator of IBM Watson and CEO at Elemental Cognition, a start-up focused on human-machine-interaction collaboration based on natural language processing understanding. Continuing these discussions between other government agencies and industry will deepen our understanding not only of the theoretical possibilities but the technological capabilities available to enable “new capabilities for doing things differently” (Corps, H. M., 2020).

**References**


**HQMC Programs & Resources (P&R)**

**NPS-21-M101-A: Ground-Based Anti-Ship Missile Effectiveness**

**Researchers:** Dr. Chad Seagren and CAPT Jeffrey Kline USN Ret.
**Student Participation:** Capt Kramer Sampson USMC

**Project Summary**
In his planning guidance documents, the Commandant of the Marine Corps states that his highest priority is future force design with a particular emphasis on improving integration with the U.S. Navy. Part of this integration envisions a key role for expeditionary forces to employ Ground-Based Anti-Ship Missiles (GBASM). We develop a scenario of a confrontation in the South China Sea between U.S. Marine forces and the People’s Republic of China. We implement that scenario in Modeling And Simulation Toolkit (MAST), an agent-based modeling platform, and employ efficient experimental design to analyze its output. We find strong evidence that a trade-off exists between missile range and launcher capacity employed in our scenario. In addition, we find that the Marine Air Defense Integrated System (MADIS) substantially improves blue survivability and operational success. Our modeling effort is likely sensitive to the tactical situation, such as the number of ships, GSABM launchers, and geography of the scenario, but the approach holds promise to similarly evaluate real-world missiles in future research. This work was greatly aided by the substantial contributions of Mary McDonald and Stephen Upton of the Simulation Experiments and Efficient Designs (SEED) Center at NPS.

**Keywords:** ground-based anti-ship missile, GBASM, anti-ship missile, expeditionary advanced base operations, EABO, littoral operations in contested environments, LOCE, combat modeling, agent-based modeling, data farming, efficient experimental design, anti-access, A2/AD
Background
The Marine Corps is in the midst of an important transformation. General Berger’s 2019 Commandant’s Planning Guidance (CPG) outlines the effort to refocus the Corps’ organization and mindset as the nation’s naval expeditionary force-in-readiness (2019). The Commandant’s highest priority is future force design with a particular emphasis on improving integration with the U.S. Navy. New concepts under development such as Expeditionary Advanced Base Operations (EABO) and Littoral Operations in Contested Environments (LOCE) support this.

EABO and LOCE play a key role for expeditionary forces to employ GBASM systems. A GBASM capability will help Navy and Marine forces transform their posture from one of deterrence-by-reactive punishment to one of deterrence-by-denial and enable them to deploy to and persist in contested areas. Such capabilities are expected to be especially important to strategic and operational success in the South China Sea and elsewhere in the United States Indo-Pacific Command (USINDOPACOM) area of responsibility.

We work closely with the sponsor to develop a scenario of a realistic confrontation in the South China Sea between U.S. Marine forces and the People’s Republic of China. The scenario is operationally plausible while providing a sufficiently rich platform to compare the effectiveness of the weapons systems under consideration. We implement the scenario in the agent-based modeling platform Modeling And Simulation Toolkit (MAST). Next, we implement the data farming techniques of highly efficient experimental designs as carried out on high-performance computers. We then apply rigorous quantitative analysis of the output data in order to answer the research questions. Sampson (2021) describes the first iteration of this process, while the corresponding technical report describes a subsequent iteration.

The objective of our project is to answer the following research questions:
1. What mixes of munitions are most effective for sea denial at varying ranges?
2. What is the impact of missile range on deterrence in South China Sea scenarios?
3. What are the benefits of various weapons mixes in coordinated attacks, especially attacks that incorporate loitering munition combinations?

Findings and Conclusions
The primary insight we gain in this phase of the project is that use of a combat model to analyze and compare missile capabilities for a given tactical scenario holds promise for future work, especially in classified space. In our scenario, given the set of notional missiles we implement, we find evidence in favor of the superiority of one missile, though identifying the best missile does require that we overcome the challenge of a multi-criteria decision. We find robust support for the notion that there is a positive relationship between the number of blue missiles fired and the proportion of blue missiles that strike their targets and that merely firing first does not appear to be an artifact of the model that drives results.

1. What mixes of munitions are most effective for sea denial at varying ranges?
   • We find blue missile range is an important factor that contributes to blue success in our scenario. However, we find that if there is a trade-off between range and launcher capacity, the best missile might not be the one with the greatest range. Similarly, the best one might not be the one with the
greatest launcher capacity. Rather, the best missile is the one that can deliver the most effective attack at the greatest range.

• We find that MADIS effectiveness is an important factor for blue survivability, namely the probability the MADIS missile strikes an incoming missile, given it was detected. With respect to denying red success, the probability that the MADIS missile detects the incoming missile is an important factor. These outcomes show that MADIS effectiveness in our model is sensitive to certain parameters, which is important to guide future modeling efforts.

• With respect to blue survivability, we find additional factors such as blue launcher move speed and red response time to be important.

• With respect to red success, we find additional factors such as red response time and the number of red missiles to be important.

2. What is the impact of missile range on deterrence in South China Sea scenarios?

• If there is a trade-off between range and launcher capacity, the best missile might not be the one with the greatest range. Similarly, the best missile might not be the one with the greatest launcher capacity.

• While missile type tends to dominate the results, there does not seem to be important interactions between missile type and other factors. In other words, a factor such as blue launcher move speed might be an important factor in some instances, but its importance does not seem to vary by missile type.

3. What are the benefits of various weapons mixes in coordinated attacks, especially attacks that incorporate loitering munition combinations?

[Redacted—see full technical report or restricted version of executive summary.]

**Recommendations for Further Research**

The most important recommendation we can give is that we believe the model and the process are ready to begin analyzing real-world missiles in classified scenarios. This project, as well as other recent theses at NPS, have demonstrated that the Modeling And Simulation Toolkit (MAST) is capable of implementing a scenario in order to generate useful insights. However, so far the insights are limited and less actionable due to the unclassified nature of the scenario and the weapons involved on either side.

We recommend future research examine the effect of degraded Command, Control, Computers, Communications, Intelligence, Surveillance and Reconnaissance (C4ISR) capability on both sides. It is clear that scouting and anti-scouting are of critical importance to Littoral Operations in Contested Environments (LOCE) and Expeditionary Advanced Base Operations (EABO) and this approach could provide valuable insight. In addition, future research should experiment with using Long Range Unmanned Surface Vehicles (LRUSVs) for tracking and targeting purposes.

Finally, we recommend future research not ignore other parts of the world where Marines that engage in EABO might employ Ground-Based Anti-Ship Missiles (GBASM) effectively, such as the Greenland-Iceland-United Kingdom gap or the Baltic region.
NPS-21-M101-B: Optimal Munitions Mix for USMC Mobile Anti-Ship Missiles Launcher

Researchers: Dr. Moshe Kress, Dr. Michael Atkinson, and Dr. Javier Salmeron-Medrano
Student Participation: Capt Aaron Barlow USMC

Project Summary
A ground-based anti-ship missile (GBASM) system is a set of tactical-level mobile missile launchers designated to maintain, from a coastal area, sea-control and sea-denial in a contested body of littoral waters. The main advantage of such an anti-ship ground-based system is its ability to hide and to scoot. Another unique characteristic of the GBASM concept, in navy operation settings, is the ability to spread the fire from a salvo across several platforms and in a manner more tailorable to a specific tactical scenario than if the salvo was delivered from a single surface ship. When designing a GBASM unit, a key question concerns the correct balance between the number of platforms (launchers) in a tactical unit and the number of missiles each platform can launch in a salvo. Fire effectiveness, survivability, and cost are the main factors that determine the optimal force design of a GBASM unit. Modeling GBASM fire engagement as a discrete-time Markov chain, we develop a methodology that evaluates the tradeoffs among number of launchers, salvo size, single-shot kill probability (SSKP), and logistical attainability of a blue GBASM unit, as dependent on red’s counter-fire effectiveness and tactics. The most notable conclusion is that the single most important factor in the outcome of the duel between a GBASM unit and an adversary ship is the size of the accumulated salvo. Notwithstanding logistical constraints, it is clear that this product should result in sufficiently high probability of killing the adversary’s ship. However, this is not a simple matter of “more is always better” because there is a point of diminishing returns, at which launchers’ capacities, logistical constraints, and costs affect decisions.

Keywords: ground-based anti-ship missile, GBASM, sea-control, sea-denial, Markov chain, force structure, salvos

Background
In 2019, the Commandant of the Marine Corps released the 38th Commandant’s Planning Guidance. This document signaled large changes to the combat formations of the United States Marine Corps and placed an emphasis on the traditional role of the Marine Corps in sea-control and sea-denial. Central to this vision is the development of a GBASM capability. This specific capability development falls under the larger umbrella of expeditionary advanced base operations (EABO), which seeks to place a persistent Marine Corps presence inside the enemy’s weapon engagement zone, to secure objectives necessary to the conduct of a naval campaign. Examples of these include potential campaigns in the South-Western Pacific and the South China Sea.
A GBASM unit comprises several ground mobile launchers, which can deliver salvos of anti-ship missiles at an enemy’s ships in the littoral waters. GBASM has two key advantages when confronting surface ships: stealth and agility. Stealth gives a GBASM unit the advantage of a first shooter, and agility facilitates an effective adoption of the shoot-and-scoot tactic.

Key force-design parameters are the number of mobile launchers in a tactical GBASM unit, the size of a single salvo by a launcher, and the missile capacity of a launcher. The last two factors, together with the shooting tactic (e.g., simultaneous firing or “leap-frogging”), determine the engagement length a GBASM unit can sustain. In particular, the questions are: If the GBASM unit consists of k launchers, each with a salvo capacity of up to s missiles, which configuration is more effective: larger k and smaller s, or the opposite—smaller k and larger s? How does the answer depend on tactics and on red’s counter-fire capabilities?

To address the aforementioned questions, we model the combat situation as a stochastic duel, and implement it as a discrete-time (absorbing) Markov chain. The absorbing probabilities are the win probabilities of blue (GBASM) and red (adversary’s ship). As such, the main thrust of our research is developing a methodology that will facilitate sound analysis of the problem. We use unclassified notional data, yet within realistic boundaries, to demonstrate the applicability of the model and to draw some initial insights and conclusions.

**Findings and Conclusions**

The model parameterizes the effective lethality (i.e., the SSKP) of GBASM missiles, which incorporates red’s capability to employ countermeasures for intercepting GBASM fire, and the enemy ship’s ability to kill GBASM platforms. These parameters affect the desired values of k, number of launchers; s, number of missiles in a single salvo by a single launcher; and the firing tactics.

The most notable conclusion is that the single most important factor in the outcome of the duel is the size of the accumulated salvo. Notwithstanding logistical constraints, it is clear that this product should result in sufficiently high probability of killing the adversary’s ship. However, this is not a simple matter of “more is always better” because there is a point of diminishing returns, at which launchers’ capacities, logistical constraints, and costs affect decisions.

Regarding the number of launchers versus missile-size tradeoff, we observe that, for a fixed product—the size of an accumulated salvo—an increased number of platforms k improves the survivability of the GBASM battery and thus its lethality. However, the magnitude of the improvement is sensitive to other parameters (e.g., SSKP) and is generally small when the salvo size is sufficiently large. This is an important observation in view of the potential cost difference between a launcher (platform, command and control systems, crew, logistical tail, etc.) and a missile.

As for tactics, the relative advantage, in terms of win probability, of simultaneous fire compared to the leap-frog tactic depends on the assumptions regarding the red ship capabilities. If red can uniformly intercept all incoming GBASM missiles and engage all GBASM launchers, then the two tactics are equally effective. However, if red’s interception rate is diminishing with the number of attacking missiles and/or it can only engage, with its counter-fire, only a subset of the GBASM launchers, then the simultaneous tactic is significantly more effective than leap-frogging. Massing fire is crucial.
This research established a methodology for quantitatively evaluating the result of an engagement between a GBASM battery and an adversary ship. It facilitates sensitivity analysis regarding the capabilities of each side and the force composition of the battery.

**Recommendations for Further Research**

A natural extension of the model is to move from the many-on-one tactical setting that is considered in our research to a many-on-many operational-level scenario where several ground-based anti-ship missile (GBASM) batteries engage several red threats. The Markov model, in this case, will likely be more complex but, we believe, reasonably tractable.

Sustaining a GBASM operation in an expeditionary advanced base operations posture is a challenge. An important future research will model the supply chain of missiles from the strategic sources in the continental United States through operational depots outside the combat zone, to the tactical resupply units of the combat forces. This research will help answer questions such as: What is the optimal missile capacity of a launcher? At which command level (e.g., battery, battalion, etc.) should the tactical resupply units be staged? What should be the missiles inventory of such a unit? Given a timeline of a typical combat scenario, what should be the acceptable logistical lead time?

**References**


**MARINE CORPS FORCES COMMAND (COMMARFORCOM)**

**NPS-21-J212-A: Performance Impacts on Unmanned Vehicle and Sensor Capabilities for Standoff Mine Detection in the Very Shallow Water, Surf Zone, and Beach Zone Environments**

**Researchers:** Dr. Joseph Klamo, Dr. Sean Kragelund, Mr. Benjamin Gozzi, and Mr. Ronan Loberg  
**Student Participation:** LT Alexander Fedorovich USN

**Project Summary**

The Navy and Marine Corps have a need to detect underwater mines and explosive ordnance from safe standoff distances in very shallow water (VSW), surf zone (SZ), and beach zone (BZ) environments. This study investigated the relationship between unmanned vehicle motion and the object detection performance of imaging sensors used for mine countermeasures. Several computer vision algorithms for automatic object detection were investigated, and the well-known Region-based Convolutional Neural Network (R-CNN) was selected. A pre-trained network was modified to detect spherical targets with an underwater camera.
Prior research on the wave-induced motion for different vehicle hull forms was used to design an apparatus for subjecting the camera to roll, pitch, and yaw motions expected in typical VSW/SZ settings. Camera motion was recorded by an inertial measurement unit, and the resulting videos were processed by the modified R-CNN algorithm to analyze the impact of platform motion on the algorithm’s object detection performance.

The R-CNN detection algorithm performed remarkably well on video imagery captured in clear water, correctly detecting a glass sphere with greater than 99% confidence whenever this object was fully visible in an image frame. The algorithm maintained this robust detection performance in every motion profile tested, even those which exceeded the wave-induced pitch angles and rates predicted for typical VSW and SZ environments. Although angular rates above the camera’s frame rate produce blurred images that reduce detection performance, these rates are much greater than underwater vehicles experience in actual maritime environments. We, therefore, conclude that in clear water, wave-induced platform motion has no effect on the object detection performance of a well-trained deep-learning algorithm processing video imagery from a camera with sufficiently high frame rate (i.e., an order of magnitude higher than vehicle pitch rates).

**Keywords:** mine, very shallow water, VSW, surf zone, SZ, beach zone, BZ, detection, sensing, standoff, unmanned, mine countermeasures, MCM, explosive ordnance disposal, EOD

**Background**

The Navy and Marine Corps conduct expeditionary warfare in very shallow water (VSW), surf zone (SZ), and beach zone (BZ) environments. Both services have a need to detect underwater hazards, mines, and explosive ordnance from safe standoff distances, but VSW/SZ/BZ environments pose severe challenges for unmanned underwater vehicles (UUVs). Breaking waves, currents, and uneven seafloor topography can produce large disturbances and unwanted vehicle motion. The goal of this study is to investigate the relationship between a vehicle’s motion and the object detection performance of imaging sensors commonly used for mine countermeasures (MCM). This study will contribute to the sponsors’ goals of understanding the capabilities and limitations of existing systems, inform future technology investment, and better define the role of each service for MCM in VSW/SZ/BZ environments.

Prior Naval Postgraduate School (NPS) research by Turner et al. (2018) and Klamo et al. (2021) examined wave-induced motion for a circular cylinder with hemispheric end caps. This canonical shape approximates the hull form of torpedo-shaped vehicles like NPS’s Hydroid REMUS 100 and the Navy’s Mk 18 UUVs used for MCM missions. Additional research by Marks (2020) analyzed the dynamic response of a remotely operated vehicle (ROV) from BlueRobotics. This platform resembles boxy, tethered vehicles like the Seabotix vLBV300 or SRS Fusion ROVs used by explosive ordnance disposal teams. These experimental results determined the range of wave-induced motions and experimental parameters used for this study.

We investigated several object detection algorithms for this project. MATLAB’s Computer Vision Toolbox was used to calibrate the underwater camera, implement well-known object detection algorithms, and assess their utility for detecting underwater mines. First, we tested an April Tag detector for finding a set of predefined fiducial markers typically used for robot localization. While not practical for MCM missions, this method provided a baseline for detecting known objects.
Next, we tested the Speeded Up Robust Features (SURF) detection algorithm normally used for three-dimensional object recognition and reconstruction. This algorithm produced numerous false positives, yet failed to reliably detect the spherical target, despite benign test conditions. Finally, we used MATLAB’s Deep Learning toolbox to implement a Region-based Convolutional Neural Network (R-CNN). We replaced the last three layers of the ResNet-18 pre-trained network with new fully connected, softmax, and classification layers, and used MATLAB’s tools to train the network to detect a spherical “mine” (glass sphere) in our training image dataset.

Two interns with the Naval Research Enterprise Internship Program and the Science & Engineering Apprentice Program worked with an NPS student to design the experimental apparatus. This test fixture was used to constrain the underwater sensor to one angular degree of freedom and subject it to different motion profiles. An inertial measurement unit recorded the sensor’s angular position, rate, and acceleration as it captured images of the spherical target in a water tank. After moving the sensor through a series of roll, pitch, and yaw motions, the resulting videos were processed by the R-CNN to assess the impact of platform motion on automatic object detection performance.

Findings and Conclusions
The R-CNN detection algorithm performed remarkably well on video imagery captured with an underwater camera in clear water. We had anticipated that large amplitude or high-frequency motion would adversely impact detection performance. However, our testing found that the R-CNN algorithm correctly detected a glass sphere with greater than 99% confidence whenever this object was fully visible in an image frame. Surprisingly, the algorithm maintained this robust detection performance in every motion profile we tested, even those which exceeded the wave-induced pitch angles and pitch rates predicted for typical VSW and SZ environments. We note that angular rates above the camera’s frame rate produce blurred images that reduce detection performance, but these rates are much greater than underwater vehicles experience in actual maritime environments. We, therefore, conclude that in clear water, wave-induced platform motion has no effect on the object detection performance of a well-trained deep-learning algorithm processing video imagery from a camera with sufficiently high frame rate (i.e., an order of magnitude higher than vehicle pitch rates). However, these results should be verified for different types of objects in operationally relevant environments.

The latter is particularly important, as MCM vehicles and sensors are unlikely to encounter benign water conditions in VSW/SZ/BZ environments. Suspended sediment, air bubbles, vegetation, and variable light conditions reduce visibility and pose significant challenges for underwater cameras. Imaging sonar provides an alternative sensing modality to potentially overcome the poor visibility of these environments, but forward-looking sonars (FLS) produce very different images—at lower frame rates—than underwater cameras do. Moreover, sonar imagery can vary greatly as a function of the target’s aspect angle relative to the sensor. It remains to be seen whether an R-CNN algorithm can be trained to reliably detect a mine-like object in FLS images generated under platform motion. We have begun analyzing this aspect dependence by generating synthetic FLS images from a simulated sonar in a three-dimensional model of our water tank and spherical target. Meanwhile, an NPS student has started to collect actual FLS imagery to train a new R-CNN detection algorithm and analyze its performance for comparison with our camera results. This project’s topic sponsors will be included on the distribution list for the completed master’s thesis.
Recommendations for Further Research
This study investigated the relationship between an unmanned vehicle’s motion and the object-detection performance of imaging sensors typically used for mine countermeasures. A deep-learning algorithm trained to detect a spherical target in underwater camera imagery was capable of successful target detection under a variety of motion profiles expected in very shallow water (VSW), surf zone (SZ), and beach zone (BZ) environments. Platform motion was found to have no effect on detection performance, but these experiments were conducted in clear water. It is important to verify these results in the desired operational settings, where decreased visibility will be a significant factor for optical cameras.

This project modified an existing convolutional neural network used for computer vision, trained it to identify a spherical target, and employed it for real-time object detection. Ongoing thesis research is applying this process to forward-looking imaging sonar. Future research should investigate whether these deep-learning algorithms, trained for one vehicle’s sensor, can be adapted to other vehicles’ sensors.

Deep-learning algorithms have greatly improved automatic target recognition algorithms used on Navy unmanned underwater vehicles. These algorithms have been trained using historical datasets collected by side-looking sonar systems on free-swimming vehicles operating primarily in VSW environments. Additional research should assess whether these algorithms can be adapted to use imagery from forward-looking sensors in SZ/BZ environments. Similarly, a future study can research ways to implement these algorithms on tethered remotely operated vehicles, bottom-crawlers, or unmanned aerial vehicles equipped with different sensors.

References


NPS-21-M181-A: Analysis of the Specifications and Capabilities for the Next-Generation LRUSV

See: NPS-21-J218-A: Long Range Unmanned Surface Vessel
NPS-21-M182-B: Counter-Unmanned Aerial Systems for the Navy and Marine Corps: Future Hardware Development Needs

Researchers: Dr. Britta Hale and Dr. Douglas Van Bossuyt
Student Participation: LCDR Boswyck Offord USN and LT Allen Golphin USN

Project Summary
Counter-unmanned aerial systems (C-UAS) technology enables detection, location, and interception of adversarial unmanned aerial systems (UAS). Use of C-UAS is not only contingent on available technology and the technology of the threat itself, but also the use-case geopolitical operational environment. The U.S. Navy and Marine Corps are tasked with providing global C-UAS defense for a multitude of mission facets to include fixed installations, forward operating bases, maritime assets, and mobile ground elements. In this context, C-UAS coordination and integration is essential to the Navy and Marine Corps’ amphibious and expeditionary warfare doctrine. This work addresses the future hardware and interoperability acquisition needs for the Navy and Marine Corps C-UAS kill chains based on existent and emerging C-UAS and UAS technologies, as well as use per areas of responsibility (AOR) during active and non-active conflicts. It applies a systems engineering approach to model C-UAS effectiveness against current and emerging threats, e.g., 5G-enabled UAS. We focus on threats imposed by smaller, handheld, commercial UASs. This work demonstrates that current C-UAS approaches and techniques will be asymmetrically ineffective against the variegated UAS threat domain and points to a necessity for interoperability among DoD-procured C-UAS to enable mission effectiveness even under current threats. This work informs and supports future requirements and concepts of operations for the Department of the Navy C-UAS and interoperability for Navy and Marine Corps C-UAS operations.

Keywords: counter-unmanned aerial systems, C-UAS, unmanned aerial systems, UAS, unmanned, security, C-UAS security, counter-unmanned systems, C-UxS, C-UxS security, geopolitical issues, C-UAS use constraints, C-UAS interoperability, C-UAS developing technology

Background
The threat imposed by commercially available, modifiable UAS can no longer be viewed as a temporary problem set. Currently, the DoD and its subsidiaries leverage and operate a plethora of over 235 C-UAS capabilities that serve as quick reaction capabilities as delineated in this research and the current C-UAS market (Holland Michel, 2018). As denoted by the Joint Counter-small unmanned aerial system Office (JCO), these capabilities cannot generate, maintain, and populate a shared common operational picture (COP) for the tactical and operational warfighter or senior decision maker to adequately address the growing UAS problem set (Jamison, 2020).

This research is in joint support of the Marine Forces Command and Navy Expeditionary Combat Command, evaluating current C-UAS employed by the USN and USMC for effectiveness and ability to interoperate. This is in turn linked to the joint C-UAS requirements created by the JCO in 2020. In 2019, the DoD issued Directive 3800.01E (Department of Defense, 2018) naming the U.S. Army as the executive agent for countering Groups 1 through 3 UAS threats domestically and abroad (Department of the Army, 2020).
Our research evaluates the UAS threat from both a maritime and ground perspective within geopolitical bounds. Understanding the adversary and their associated offensive capabilities and limitations allows for the best assertion of what defensive capabilities and level of force are required to protect, defend, and conduct counter-offensive operations where applicable.

Our research uniquely defines the threat actors who operate Groups 1 through 3 UASs with the National Intelligence Council definition of hobbyist, state, and non-state actors (National Intelligence Council, 2007). We measure the extent of damage adversarial UAS applications have conducted in every AOR. Our research uses this information to identify what means of command and control (C2) are leveraged in every AOR to support adversarial UAS flight and payload operations. The means of C2 accessible in an AOR is calculated into the assessment of what actions adversaries are able to conduct currently with commercial off-the-shelf UASs, as well as what adversaries will be able to execute with emergent technology, infrastructure, and innovation.

Our research then investigates the current C-UAS capabilities recommended by the JCO and employed by the USN and USMC to support countering UASs. We evaluate the degree of effectiveness associated with specific C-UAS capabilities leveraged to support identifying and neutralizing varying numbers of UAS threats. We implement and leverage system engineering models using constructed data for demonstration to simulate the rate of effectiveness and the level of interoperability with other subsidiary C-UAS subsystems needed to support the C-UAS kill chain.

This work represents the input and collaboration of the principle investigator (PI) and Co-PI, student researchers, sponsors, and Strategic Weapons Facility Pacific (SWFPAC). LT Offord and LT Golphin produced their thesis research under the project umbrella. NPS and SWFPAC collaboration on C-UAS was initiated under the project umbrella and continues along the further research lines recommend below.

**Findings and Conclusions**

Our research concludes on the discernment of legal limitations imposed upon existing and emergent C-UAS capabilities needed to support the C-UAS kill chain against UAS threats. Our unique application of radio frequency (RF) deconfliction methods, procedures, and capabilities further delivers the potential for understanding the extent of C-UAS capabilities’ active emission applications in an AOR. Further, we delineate Advanced Refractive Effects Predication System, Real-Time Spectrum Operations, Own Force Monitoring, and Builder as predictive analysis tools capable of supporting RF deconfliction and approval to operate existing and emergent C-UAS capabilities, as well as determine how effective C-UAS capabilities will be if applied to a specific area, weather, or terrain.

The operational environment is saturated with both UAS and C-UAS products with increased use by adversarial operators. There remains an emergent need to establish requirements for the USN and USMC to conduct joint, interoperable C-UAS operations against Groups 1 through 3 UAS threats. We observe the effectiveness of current USN and USMC C-UAS capabilities could worsen as more UASs are operated in AORs with advanced technology. To meet the demand of joint C-UAS requirements, the USN and USMC must divest from the previous mentality of interim solutions to a permanent problem. Long-term, interoperable C-UAS solutions that are capable of performing the high rates of effectiveness against today's and future UAS threats are needed.
Recommendations for Further Research

The following list encapsulates suggested recommendations to improve counter-unmanned aerial system (C-UAS) interoperability and effectiveness in the geopolitical environment:

1. Establish a common baseline architecture to be used as the foundation for the Department of the Navy C-UAS. This should include configuration management for evolving software and change management for requirements or mission shifts.

2. Integrate spectrum analysis tools such as Advanced Refractive Effects Predication System, Real-Time Spectrum Operations, or Builder into existing and future C-UAS capabilities and planning to improve radar and radio frequency (RF) detection, tracking, and neutralization techniques. This should include leveraging spectrum analysis tools to compute and display passive RF probability of detection in varying weather and terrain environments, as well as leveraging spectrum analysis tools to support the prediction of fratricide, minimization of electromagnetic interference and legal deconfliction for host nation employment.

3. Acquire and implement C-UAS capabilities with high probability of detection at extended ranges, interoperability with the Joint Counter-small unmanned aerial system Office mandated Forward Area Air Defense Command and Control architecture, and high probability of detection for increased numbers of simultaneous unmanned aerial system (UAS) targets (such as clusters and swarms).

4. Conduct site surveys and blue force laydown to support accurate sensor placement to account for multi-domain threat axis, geometry for the terrain, and friendly force emissions.

The threat UASs pose today is here to stay and will soon likely worsen. The suggested recommendations are provided as a protective measure for Department of Defense interests against current and emerging UAS threats.

Additional research is recommended on integration of new techniques such as machine learning and other cyber capabilities into emergent C-UAS to enhance detection and mitigation and support the promulgation of UAS threat libraries. Adversarial machine learning must necessarily be considered alongside any such architectures. Additionally, understanding how terrain impacts the UAS tactics, techniques, and procedures (TTPs) leveraged by adversaries may show the subsequent need for C-UAS terrain-based TTPs to counter adversaries. As part of this, research is recommended on C-UAS concepts of operation to identify potential gaps and opportunities in leveraging novel C-UAS techniques so as to reduce the UAS/C-UAS threat response asymmetry.

References


NPS-21-M187-B: DMO Tactical Grid – Edge Processing, Mission Analytics, Officer Qualification

See: NPS-21-J087-A: DMO Tactical Grid – Edge Processing, Mission Analytics, Officer Qualification

MARINE CORPS SYSTEMS COMMAND (MARCORSYSCOM)

NPS-21-M079-B: Training Intelligent Red Team Agents Via Reinforcement Deep Learning

Researcher: Dr. Marcus Ballard
Student Participation: No students participated in this research project.

Project Summary
Wargames are an essential tool for education, training, and formulation of strategy. They are especially important in the evaluation of threats from, and strategies against, trained adversaries who present significant risk to friendly forces. We proposed to develop a wargame adversary trained to defeat the current strategy of friendly forces, allowing the evaluation of alternate strategies against an intelligent, simulated opponent. This research sought to evaluate the ability of different deep neural network algorithms to train an enemy red team against a friendly blue team with an existing strategy, in terms of both efficacy and efficiency, and the resiliency of the trained red team to subsequent changes in blue team strategy.

A simulated combat environment was created in which a blue team was first trained using deep reinforcement learning (DRL) to defeat a stationary opponent in an open battlefield, establishing a baseline blue strategy. The red team was then trained, again with DRL, to defeat this blue team, after which the blue team’s strategy was altered, and the two teams were allowed to engage in combat again. During this experiment, the time required to train the red team and the proportion of combat outcomes that red won were calculated and later analyzed. Several important variables were identified, from both the combat environment and the algorithms employed to train each team, that significantly affected the time required to train the red team and the red team’s subsequent ability to win against an opponent with an altered strategy. Additionally, it was determined that while there was no significant difference between the algorithms in the meantime required for red team training, the choice of algorithm had a significant effect on the red team’s subsequent ability to win against an opponent whose strategy differs from the one against which it was trained.
Keywords: wargames, simulations, deep reinforcement learning, DRL

Background
Wargames are common across military domains but are particularly relevant to fields that may come into contact with enemy forces, such as combat arms. Historically, humans have played the role of both friendly (blue) and enemy (red) forces when conducting wargames. This study is an initial step toward developing an artificial intelligence (AI) red team that can be trained to overcome an existing strategy—say, the current strategy of the blue team. Such a red team could then be used to examine where current strategy fails and to test new strategies.

One powerful approach to developing AI agents is the use of DRL, which uses neural networks constructed with one or more hidden layers to train AI agents to learn (near) optimal behavior by maximizing the reward obtained in a pre-defined environment. There is an ongoing international effort to apply AI in general, and DRL in particular, to military wargames. Moy & Shekh (2019) investigated the ability of combining AlphaZero DRL and supervised learning to automatically learn to play wargames. Wang et al. (2020) investigated the large-scale use of DRL in wargames. Zhang and Xue (2020) proposed an actor-critic framework for AI decision making using Convolutional Neural Networks. Lucek and Collander-Brown (2017) proposed decision-making software that uses AI to allocate “forces in space and time in order to achieve a particular objective, in a situation of partial knowledge and where the enemy is also planning and reacting,” and Goodman et al. (2020) wrote a comprehensive reference paper detailing the use of AI in military wargames. The US Army has developed prototype wargaming software that uses AI to recommend course of action improvements to commanders and staff (Schwartz et al., 2020), while US Navy researchers have conducted simulations to test various DRL algorithms’ ability to train red team agents (Boron & Darken, 2020). In Boron and Darken’s (2020) experiment, a small group of mobile red team agents was allowed to learn attacking behavior using DRL against stationary blue team agents.

In this work, we sought to determine how changes in scale and other training-specific variables might affect the time required to train AI agents and their ability to win in combat, as measured by training time and win rate, respectively, within a simulated wargame environment. A three-stage framework was developed in which a red team learned to defeat a pre-trained blue team and were then evaluated on how well they were able to overcome subsequent changes to the blue team’s strategy.

Statistical software was used to design an experiment that would allow us to identify significant relationships between training time, win rate, and the individual variables under consideration. Once the experiment was complete, linear models were built to evaluate the effects of the experiment variables on training time and win rate. Two such models that did not take the training algorithm used into account were built for training time and win rate. Then, for both training time and win rate, an additional model was created to evaluate individual training algorithms.

Findings and Conclusions
We found that while there was no difference in mean training time between the three algorithms examined in this experiment, Trust Region Policy Optimization produced significantly higher win rates on average than Proximal Policy Optimization or Vanilla Policy Gradient.
The choice of training algorithm appears to be a significant factor in the AI red team’s ability to win in subsequent matches, particularly against a blue team whose strategy may be changing.

We were unable to find any significant relationship between the time spent training the red team and the red team’s win rate in subsequent matches against a blue team with an altered strategy. However, we have outlined some potential reasons for this phenomenon and suggest additional research.

Generally, the red team’s ability to win matches was not affected by changes in the blue team’s strategy. Changes in blue team strategy negatively affected the red team’s ability to win only when the red team was trained using the Proximal Policy Optimization algorithm. This effect was quite large, though, and so cannot be easily overlooked.

Training the red team using a deterministic combat adjudication model also tended to significantly increase the win rate in subsequent matches, whether those matches were adjudicated with a deterministic or a stochastic model, with little effect on training time. The red team’s ability to win in subsequent matches was also positively affected by a larger red team size and negatively affected by a larger blue team size or simulation map size.

Overall, we found the AI red team to be fairly resistant to changes in blue team strategy but highly sensitive to changes in the simulation environment. We found several environment-specific variables that would have a significant effect on the time required to train the red team and the ability of the red team to win against a changing blue team. Increasing the red team size tends to lengthen training time but improves the win rate. Increasing the blue team size also increases training time but leads to a lower win rate. Likewise, increasing the size of the simulation map increases training time and lowers the red team’s subsequent win rate.

We also identified several algorithm-specific variables that significantly affected the red team’s training time and subsequent win rate, and some variables that did not. Decreasing the number of training iterations, increasing the amount by which the algorithms can learn from each training iteration and/or increasing neural network structure size decreased training time with minimal effect on win rate. Training the red team using a deterministic model for adjudicating combat also tends to increase the red team’s win rate in subsequent matches, whether those matches are adjudicated with a deterministic or stochastic model, with little effect on the red team’s training time. Some variables, such as the amount by which the blue team’s strategy could change and the weight the algorithms put on short-term gains versus long-term gains, did not have a significant effect on either training time or win rate.

**Recommendations for Further Research**

This research was conducted on a simulated, open battlefield with agents on both teams seeking only to destroy the other team. We recommend that the research be expanded to include more sophisticated terrain such as impassable areas, areas that slow movement, and areas that impede vision/communication. Agents’ abilities can be made more diverse to more closely mimic the variety of abilities found in actual combat units, such as artillery, tanks, and, if appropriate, aircraft and seacraft. All agents within this simulation had a single mission: search for and destroy the opposing team. Future research could extend to more complicated goals such as infiltration without detection, location and retrieval of an item, and defense of an item or area.
We limited the architecture of the neural networks employed in this research, but neural networks can take on a variety of sophisticated architectures which may prove informative in future research. Finally, the algorithms used for deep reinforcement learning (DRL) in this research were selected to be representative of algorithms commonly used in DRL research and applications. However, there are other algorithms—many entirely free of neural networks—that could be employed, and their performance evaluated against this work.

References
# List of Abbreviations and Acronyms

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>5G NR</td>
<td>Fifth generation cellular - new radio</td>
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<tr>
<td>A2/AD</td>
<td>Anti-access/area denial</td>
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<td>ABM</td>
<td>Anti-Ballistic Missile Treaty</td>
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<td>ACINT</td>
<td>Acoustic intelligence</td>
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<td>ACOMDR</td>
<td>Automated Cyber Operations Mission Data Replay</td>
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<td>ADMITS</td>
<td>Alcohol and Drug Management Information Tracking System</td>
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<td>ADRAM</td>
<td>Airframe Depot Readiness Assessment Model</td>
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<td>ADSM</td>
<td>Active-duty service member</td>
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<tr>
<td>AEOG</td>
<td>Automatic Electrolytic Oxygen Generator</td>
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<tr>
<td>AFSIM</td>
<td>Advanced Framework for Simulation, Integration, and Modeling</td>
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<td>AGI</td>
<td>Ad hoc gain inversion</td>
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<tr>
<td>AHP</td>
<td>Analytical Hierarchy Process</td>
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<td>AI</td>
<td>Artificial intelligence</td>
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<tr>
<td>AI/ML</td>
<td>Artificial intelligence/machine learning</td>
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<td>Block Definition Diagram</td>
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<td>Big Data Platform-Cyber Hunt &amp; Analytics Operation System</td>
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<td>Critical command decision</td>
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<td>CONOPS</td>
<td>Concept of operations</td>
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<td>Cognitive radio</td>
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<td>C-UAS</td>
<td>counter-unmanned aerial systems</td>
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<td>carrier air wing</td>
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<td>denied, disrupted, intermittent, and limited (bandwidth)</td>
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<td>Department of Defense</td>
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<td>DoDADF</td>
<td>Department of Defense Architecture Framework</td>
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<td>design of experiments</td>
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<td>Department of the Navy</td>
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<td>DOT</td>
<td>Department Officer Tour</td>
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<td>DOTMLPF</td>
<td>doctrine, organization, training, material, leadership, personnel, and facilities</td>
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<td>design point</td>
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<td>digital twin network</td>
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<td>Expeditionary Advanced Base Forces</td>
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<td>EABO</td>
<td>Expeditionary Advanced Base Operations</td>
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<td>European Centre for Medium-Range Weather Forecasts</td>
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<td>excessive daytime sleepiness</td>
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<td>electronic intelligence</td>
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<td>expendable mobile anti-submarine-warfare training target</td>
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<td>EMCON</td>
<td>Emissions Control</td>
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<td>EMP</td>
<td>electromagnetic pulse</td>
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<td>EO</td>
<td>electro-optical</td>
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<td>EPF</td>
<td>Expeditionary Fast Transport</td>
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<td>Exponential Random Graph Model</td>
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<td>ESG</td>
<td>Expeditionary Strike Group</td>
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<td>ESPC</td>
<td>Earth Systems Prediction Capability</td>
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<td>EUL</td>
<td>Enhanced Use Lease</td>
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<td>Federal Aviation Administration</td>
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<td>flashbang grenade</td>
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<td>FLS</td>
<td>forward-looking sonar</td>
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<td>forward operating base</td>
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<td>foreign national</td>
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<td>Fleet Replacement Squadron</td>
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<td>FSCn</td>
<td>fire support coordination</td>
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<td>Future Years Defense Plan</td>
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<td>generative adversarial network</td>
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<td>GBASM</td>
<td>ground-based anti-ship missile</td>
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<td>Gbps</td>
<td>gigabits per second</td>
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<td>GNAR</td>
<td>generalized network autoregressive</td>
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<td>GPC</td>
<td>Great Power Competition</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>General Systems Theory</td>
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<td>high-altitude balloon</td>
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<td>Hadoop Distributed File System</td>
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<td>high frequency</td>
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<td>Hyperledger Fabric</td>
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<td>human-machine teaming</td>
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<td>hyperspectral</td>
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<td>interdependence analysis</td>
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<td>IAMD</td>
<td>integrated and missile defense</td>
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<td>intelligence community</td>
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<td>independent duty corpsman</td>
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<td>IDS</td>
<td>intrusion detection system</td>
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<td>information environment</td>
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<td>Introductory Flight Screening</td>
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<td>Internet Gaming Disorder</td>
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<td>Integrated Low Pressure Electrolyzer</td>
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<td>IMEC</td>
<td>Item Mission Essentials Code</td>
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<td>INDOPACOM</td>
<td>Indo-Pacific Command</td>
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<td>INF</td>
<td>Intermediate-Range Nuclear Forces Treaty</td>
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**Note:** The abbreviations listed are specific to the Naval Research Program FY21 Annual Report. Other abbreviations may be used in different contexts or for different purposes.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<td>INS</td>
<td>Inertial Navigation System</td>
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<td>IOC</td>
<td>initial operating capability</td>
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<td>initial operational position</td>
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<td>Integrated Prioritized Capabilities List</td>
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<td>Infrared</td>
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<td>ISR</td>
<td>Intelligence, Surveillance, and Reconnaissance</td>
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<td>information warfare</td>
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<td>JADC2</td>
<td>joint all-domain command and control</td>
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<td>JAIC</td>
<td>Joint AI Center</td>
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<td>JCA</td>
<td>Joint Campaign Analysis</td>
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<td>JCN</td>
<td>Job Control Number</td>
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<td>Joint Counter-small unmanned aerial system Office</td>
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<td>JIFCO</td>
<td>Joint Intermediate Force Capabilities Office</td>
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<td>JOC</td>
<td>joint operations center</td>
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<td>Knowledge Flow Theory</td>
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<td>Kelp Road Initiative</td>
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<td>LAILLOW</td>
<td>leverage AI to learn, optimize, and win</td>
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<td>Littoral Combat Ship</td>
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<td>LLA quantum intelligence game</td>
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<td>Learning Management System</td>
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<td>littoral operations in contested environments</td>
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<td>low probability of detection</td>
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<td>amphibious transport dock</td>
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<td>LPE</td>
<td>Low Pressure Electrolyzer</td>
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<td>LRHW</td>
<td>Long-Range Hypersonic Weapon</td>
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<td>LRUSV</td>
<td>Long Range Unmanned Surface Vessel</td>
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<td>lighter-than-air</td>
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<td>laser weapon system</td>
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<td>Master of Applied Cyber Operations</td>
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<td>Marine Air Defense Integrated System</td>
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<td>Map Aware Non-uniform Automata</td>
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<td>MCDM</td>
<td>multi-criteria decision-making</td>
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<td>mine countermeasures</td>
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<td>Medium Displacement Unmanned Surface Vessel</td>
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<td>Methodology for Employing Architecture for Systems Analysis</td>
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<td>Meteorological and Oceanographic</td>
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<td>mixed integer linear program</td>
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<td>multiple-input/multiple-output</td>
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<td>machine learning</td>
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<td>multiple launch rocket system</td>
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<td>MOE</td>
<td>measure of effectiveness</td>
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<td>mean time between failures</td>
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<td>National Item Identification Numbers</td>
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<td>near infrared</td>
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<td>natural language processing</td>
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<td>non-mission capable supply</td>
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<td>National Oceanic and Atmospheric Administration</td>
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<td>Nearly Orthogonal Hyper Cube</td>
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<td>Naval Research Program</td>
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<td>Naval Special Warfare</td>
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<td>Naval Special Warfare Command</td>
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<td>Offensive Cyber Operations</td>
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<td>Optical Character Recognition</td>
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<td>Orthogonal Frequency Division Multiplexing</td>
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<td>Office of Naval Intelligence</td>
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<td>Observability, Predictability, and Directability</td>
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<td>On-Station Time</td>
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<td>P/PM</td>
<td>Performance/Pricing Model</td>
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<td>P-ALT</td>
<td>Pre-Attainment Lead Time</td>
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<td>Phased Array Sweep Listening</td>
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<td>Persistent Cyber Training Environment</td>
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<td>Partner Forces</td>
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<td>Principal Investigator</td>
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<td>Probable Impact Point</td>
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<td>Precision Landing Mode</td>
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<td>Planned Maintenance Interval</td>
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<td>Personal Protective Equipment</td>
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<tr>
<td>PRA</td>
<td>Probability of Raid Annihilation</td>
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<tr>
<td>RAATM</td>
<td>Resetting Anchor Antenna Tether Mechanism</td>
</tr>
<tr>
<td>RAM</td>
<td>Reliability, Availability, Maintainability</td>
</tr>
<tr>
<td>R-CNN</td>
<td>Region-based Convolution Neural Network</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFI</td>
<td>Ready for Issue</td>
</tr>
<tr>
<td>ROKA</td>
<td>Republic of Korea Army</td>
</tr>
<tr>
<td>ROP</td>
<td>Re-order Point</td>
</tr>
<tr>
<td>ROV</td>
<td>Remotely Operate Vehicle</td>
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<tr>
<td>RRL</td>
<td>Ready, Relevant Learning</td>
</tr>
<tr>
<td>RSAF</td>
<td>Republic of Singapore Air Force</td>
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<tr>
<td>S2S</td>
<td>Sub-seasonal to Seasonal</td>
</tr>
<tr>
<td>SA</td>
<td>Situational Awareness</td>
</tr>
<tr>
<td>SACC</td>
<td>Supporting Arms Coordination Center</td>
</tr>
<tr>
<td>SAG</td>
<td>Surface Action Group</td>
</tr>
<tr>
<td>SARP</td>
<td>Substance Abuse Rehabilitation Program</td>
</tr>
<tr>
<td>SATCOM</td>
<td>Satellite Communications</td>
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<tr>
<td>SDR</td>
<td>Software-defined Radio</td>
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<tr>
<td>SECREP</td>
<td>Secondary Repairable Materiel</td>
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<tr>
<td>SEED</td>
<td>Simulation Experiments &amp; Efficient Designs</td>
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<tr>
<td>SER</td>
<td>Symbol Error Rate</td>
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<tr>
<td>SFC</td>
<td>Single Fuel Concept</td>
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<tr>
<td>SGAN</td>
<td>Semi-supervised Generative Adversarial Network</td>
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<tr>
<td>SHA</td>
<td>Schedule Health Assessment</td>
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<tr>
<td>SIGINT</td>
<td>Signals Intelligence</td>
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<tr>
<td>SME</td>
<td>Subject Matter Expert</td>
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<tr>
<td>S-MIP</td>
<td>Schedule Mixed Integer Program</td>
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<tr>
<td>SMWDC</td>
<td>Naval Surface and Mine Warfighting Development Center</td>
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<tr>
<td>SNA</td>
<td>Social Network Analysis</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SOF</td>
<td>Special Operations Forces</td>
</tr>
<tr>
<td>SOI</td>
<td>Signal of Interest</td>
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<tr>
<td>SoS</td>
<td>Systems of Systems</td>
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<tr>
<td>SRA</td>
<td>Schedule Risk Assessment</td>
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<tr>
<td>SSAG</td>
<td>Space Systems Academic Group</td>
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<tr>
<td>SSKP</td>
<td>Single Shot Kill Probability</td>
</tr>
<tr>
<td>SSPK</td>
<td>Single-shot Probability of Kill</td>
</tr>
<tr>
<td>STORM</td>
<td>Synthetic Theater Operations Research Model</td>
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<tr>
<td>sUAS</td>
<td>Small Unmanned Aerial System</td>
</tr>
<tr>
<td>SubX</td>
<td>Subseasonal Experiment</td>
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<tr>
<td>SURF</td>
<td>Speeded Up Robust Features</td>
</tr>
</tbody>
</table>
**LIST OF ABBREVIATIONS AND ACRONYMS CONT…**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>SWF-PAC</td>
<td>Strategic Weapons Facility Pacific</td>
</tr>
<tr>
<td>SWIFT</td>
<td>Standard Wargame Integration and Facilitation Tool</td>
</tr>
<tr>
<td>SWIG</td>
<td>Sea Wing in Ground</td>
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<tr>
<td>SWO</td>
<td>Surface Warfare Officer</td>
</tr>
<tr>
<td>SysML</td>
<td>Systems Modeling Language</td>
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<tr>
<td>SZ</td>
<td>surf zone</td>
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<tr>
<td>T/M/S</td>
<td>type, model, series of aircraft</td>
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<tr>
<td>TAT</td>
<td>turn-around time</td>
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<tr>
<td>TCPED</td>
<td>tasking, collection, processing, exploiting and dissemination</td>
</tr>
<tr>
<td>TLA</td>
<td>Total Learning Architecture</td>
</tr>
<tr>
<td>TMR</td>
<td>transportation movement request</td>
</tr>
<tr>
<td>TMS</td>
<td>type/model/series</td>
</tr>
<tr>
<td>TOPSIS</td>
<td>Technique for Order Preference by Similarity to Ideal Solution</td>
</tr>
<tr>
<td>TPA</td>
<td>technical performance analysis</td>
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<tr>
<td>TRL</td>
<td>technology readiness level</td>
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<tr>
<td>T-SHARP</td>
<td>Training Sierra Hotel Aviation Readiness Program</td>
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<tr>
<td>TSSE</td>
<td>Total Ship Systems Engineering</td>
</tr>
<tr>
<td>TTP</td>
<td>tactics, techniques, and procedures</td>
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<tr>
<td>UAS</td>
<td>unmanned aerial system</td>
</tr>
<tr>
<td>UAV</td>
<td>unmanned aerial vehicle</td>
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<tr>
<td>UECP</td>
<td>user-side equipment connection process</td>
</tr>
<tr>
<td>USINDOPACOM</td>
<td>United States Indo-Pacific Command</td>
</tr>
<tr>
<td>USMC</td>
<td>United States Marine Corps</td>
</tr>
<tr>
<td>USN</td>
<td>United States Navy</td>
</tr>
<tr>
<td>USNI</td>
<td>United States Naval Institute</td>
</tr>
<tr>
<td>USNINT</td>
<td>United States Naval Institute</td>
</tr>
<tr>
<td>USSOCOM</td>
<td>United States Special Operations Command</td>
</tr>
<tr>
<td>USV</td>
<td>unmanned surface vessel</td>
</tr>
<tr>
<td>USVs</td>
<td>unmanned surface vessels</td>
</tr>
<tr>
<td>UUV</td>
<td>unmanned underwater vehicle</td>
</tr>
<tr>
<td>UVC</td>
<td>unmanned vehicle carrier</td>
</tr>
<tr>
<td>UXO</td>
<td>unexploded ordinance</td>
</tr>
<tr>
<td>UxV</td>
<td>unmanned vehicle</td>
</tr>
<tr>
<td>VCN</td>
<td>Vice Chief of Naval Operations</td>
</tr>
<tr>
<td>VG</td>
<td>Video game</td>
</tr>
<tr>
<td>VHF</td>
<td>very-high frequency</td>
</tr>
<tr>
<td>VLS</td>
<td>Vertical Launch System</td>
</tr>
<tr>
<td>VNIR</td>
<td>visible and NIR</td>
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<tr>
<td>VOI</td>
<td>value-of-information</td>
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<tr>
<td>VSW</td>
<td>very shallow water</td>
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<tr>
<td>WASPA</td>
<td>Weighted Aggregated Sum Product Assessment</td>
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<tr>
<td>WIEVLE</td>
<td>Wreck Interior Exploration Vehicle</td>
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<tr>
<td>WIP</td>
<td>Warfare Improvement Programs</td>
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<tr>
<td>WPM</td>
<td>Weighted Product Model</td>
</tr>
<tr>
<td>WRENCH</td>
<td>Workbench for refining Rules of Engagement against Crowd Hostiles</td>
</tr>
<tr>
<td>WSG</td>
<td>Weapon System Group</td>
</tr>
<tr>
<td>WSM</td>
<td>Weighted Sum Mode</td>
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</table>