NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

CONSORTIUM FOR ROBOTICS AND UNMANNED SYSTEMS EDUCATION AND RESEARCH (CRUSER)

2021 ANNUAL REPORT

by

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Prepared for:
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Director, Code 32, Office of Naval Research

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14. ABSTRACT

The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems (UxS) education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest on the application of unmanned systems (UxS) in military and naval operations. This 2021 annual report summarizes CRUSER activities in its tenth year of operations and highlights future plans.

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TABLE OF CONTENTS

I. INTRODUCTION

A. Background

The Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) provides a collaborative environment and community of interest for the advancement of unmanned systems education and research endeavors across the Navy (USN), Marine Corps (USMC) and Department of Defense (DoD). CRUSER is a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest on the application of unmanned systems in military and naval operations. Funding for seed research activities is provided by the Office of Naval Research, other activities are funded by a variety of sources. CRUSER encompasses the successful research, education, and experimentation efforts in unmanned systems currently ongoing at NPS and across the naval enterprise.

B. Vision

At the direction of the SECNAV, NPS leverages its long-standing experience and expertise in research and education related to intelligent autonomous systems (IAS) in support of the naval mission. The CRUSER program grew out of the SECNAV's unmanned systems prioritization, and concurrent alignment of unmanned systems research and experimentation at NPS. CRUSER serves as a vehicle by which to align currently disparate research efforts and integrate academic courses across domain and discipline boundaries with the DON Unmanned Campaign Framework DON Science and Technology Strategy for IAS.

CRUSER is a facilitator for the Navy's common research interests in current and future unmanned systems and robotics. The Consortium, working in partnership with other organizations, will continue to inject a focus on IAS into existing joint and naval research and field experiments as well as host specific events, both experimental and educational.

Furthermore, with the operational needs of the Navy and the Marine Corps at its core, CRUSER will continue to be an inclusive, active partner for the effective education of future military leaders and decision makers. Refining existing courses of education and designing new academic programs is an important benefit of CRUSER, making the Consortium a unique and indispensable resource for the Navy while highlighting the educational mission of NPS. Specific CRUSER goals continue to be:

- Shape generations of naval officers through education, research, concept generation and experimentation in maritime application of robotics, automation, and unmanned systems.
- Provide a source for unmanned systems employment concepts for operations and technical research.
- Provide an experimentation program to explore unmanned system employment concepts.
- Provide a venue for Navy-wide education in intelligent, autonomous systems.
- Provide a DoD-wide forum for collaborative education, research, and experimentation in unmanned systems.

CRUSER takes a holistic approach to address issues related to naval unmanned systems research and employment, from technical to ethical and concept generation to experimentation. A variety of research areas inform and augment traditional technical research in unmanned systems, and aid in their integration into fleet operations.

C. Management

CRUSER is organized as an NPS research project except with a more extensive charter than most reimbursable projects. It has both an oversight organization and coordination team. The Director, with the support of a lean research and administrative staff, leads CRUSER and executes the collaborative vision for the Consortium. The Director encourages, engages, and enhances on-campus efforts among all four graduate schools and existing centers and institutes. Faculty and students from all curricula with an interest in the development of unmanned systems are encouraged to contribute and participate. Furthermore, the CRUSER advisory group (CAG), consisting of the CRUSER directors, Dean of Research, warfare chairs and on-campus senior officers from each military service, provides high-level direction to balance academic, S&T and warfighting perspectives. This group ensures that the Fleet and its operations remain a primary consideration in CRUSER activities to include the selection of activities supported by CRUSER.

II. SEED RESEARCH PROJECTS

The CRUSER Seed Research Program (SRP) is a critical aspect of how CRUSER achieves this objective. The program provides an environment for students, faculty, and staff to collaborate both internally and externally with the common goal of accelerating the development and fielding of unmanned systems across the DON. Furthermore, the SRP functions as an incubator, providing initial support for the NPS community to explore new, relevant concepts with the potential to transition to externally supported NPS research program.

CRUSER research provides an authentic academic experience for NPS students within the many fields that constitute Intelligent Autonomous Systems (IAS) science and technology. CRUSER continues to support a wide diversity of research topics, "from technical to ethical, from concept to experiment". CRUSER prioritizes support for seed projects that have a clear transition path for follow-on external support, e.g., research grant support, fleet investment, etc.

CRUSER supports both fundamental research (both basic and applied), "the results of which ordinarily are published and shared broadly within the scientific community,"1 and development, design, production, and product utilization efforts, the results of which ordinarily are restricted or classified or national security reasons. Table 1 summarizes the 15 CRUSER seed research projects for 2021 and the following subsections are detailed summaries of each project.

Table 1: 2021 CRUSER Seed Research Projects

	Principal Investigator(s)	Project Title
1	Prof. Leo Blanken Prof. Justin Davis	COTS Unmanned Systems and Partner Force Innovation
2	Prof. Christopher Brophy Prof. Joshua Codoni	Counter Aerial UxS Munition Delivery System
3	Prof. Don Brutzman Prof. Curtis Blais	Ethical Control of Unmanned Systems: Repeatable Mission Evaluation Through Unmanned Systems Data Strategy for UMAA/RAIL
4	Prof. Anthony (Mustafa) Canan Prof. Mustafa Dumir (ASU)	Communication Dynamics of Human-Machine Teams in Context Sensitive Battle-Field Environment
5	Prof. Abram Clark Prof. Isaac Kaminer	Developing Operational Planning Simulations for Defense Against Attacking Drone Swarms
6	Prof. Duane Davis Prof. Kevin Jones	Expediting Swarm System Development with High Fidelity Live/Virtual Modeling and Simulation

	Prof. Katy Giles, CDR, USN	
7	Kristen Fletcher Eric Hahn	Priority Legal and Policy Issues of UxS
8	Prof. Douglas Horner Prof. Geoffrey Xie Prof. Ruriko Yoshida	Behavior Automation for UxV Networked Control Systems
9	Prof. Kevin Jones Prof. Vladimir Dobrokhodov Dr. Paul Leary Prof. Kevin Smith	Aqua-Quad Vector Sensor Integration and Participation in Trident Warrior 2021
10	Prof. Sean Kragelund Prof. Isaac Kaminer	Hybrid USV Attacks for Counter-Swarm Experimentation
11	Prof. Jim Newman Giovanni Minelli	Predictive Failure Analysis for Autonomous Networked Ground Stations
12	Prof. Douglas Van Bossuyt Prof. Robert Semmens Kristen Fletcher Kristin Weger Bryan Mesmer Nathan Tenhundfeld Nicholaos Jones	Formation, Implementation, and Verification of Requirements for Human-Autonomy Teaming
13	Prof. Qing Wang Ryan Yamaguchi	sUAS-based Environmental Sampling in Support of High Energy Laser Weapon Systems
14	Prof. Xiaoping Yun Prof. James Calusdian	Localization of Unmanned Ground Systems Using the Zero Velocity Update Technique and a 3-D LiDAR in the Absence of GNSS
15	Prof. Oleg Yakimenko	Enhancing c-UAS Capabilities using a 3D LiDAR

A. COTS Unmanned Systems and Partner Force Innovation

Participants

- Principal Investigator (PI): Leo Blanken ljblanke@nps.edu
- Co-PIs:
  Justin Davis justin.p.davis@nps.edu
- Students:
  Major Romulo Dimayuga (Philippines Marine Corps)

Major Goals

This initial project focused on the work of Romulo Dimayuga's thesis project, entitled "Commercial-Off-the-Shelf Drone Design: A Rapid Equipage Alternative for Force Recon Companies." Major Dimayuga, a Marine from the Philippines, came to NPS with the passion to fill a capability gap for his home unit – an affordable, sustainable, unmanned aerial system that would provide short-range reconnaissance tailored specifically to the tactical needs of the Filipino Force Recon Marines. His units needed such a "home grown" system, because the American systems (Raven, Puma) were controlled by higher echelons and were frequently not available for the Marines at the Company level. Working with NPS faculty and the campus RoboDojo, Romulo sought to design a basic prototype of such a system.

Accomplishments:

- Major Dimuyuga graduated with "Distinction" from the Defense Analysis Department
- Major Dimayuga earned an "Outstanding Thesis" Award for his project
- Major Dimayuga was awarded the "Naval Postgraduate School Outstanding Academic Achievement Award for International Students"

Education:

Completed:

- Dimayuga, Romulo. 2020. COTS Drone Design: A Rapid Equipage Alternative for Force Recon Companies. Naval Postgraduate School Thesis.

Ongoing:

- Ernest Jadloc (JUN 2022) and Joel Bonavente (DEC 2022) are students from the Philippines who are pursuing follow-on projects to fill indigenous capability gaps.
- Michael Scott Rowen (DEC 2022) and Patrick Foley (DEC 2022) are US Special Operations Forces (USSOF) students who are exploring how this line of effort can fit within doctrine for ARSOF Security Force Assistance (SFA) efforts.

Dissemination:

- The project was briefed to Deputy CG of US Army Pacific Command (MG Johnathan Braga), who is now the CG of US Army Special Operations Command.
- The project was briefed to the Commanding General of the US Army John F Kennedy Special Warfare Center and School (MG Patrick Roberson).

- An article was published by the student and advising team (Romulo Dimayuga, Leo Blanken, and Kristen Tsolis) in War on the Rocks: "Making Friends in Maker Spaces: From Grassroots Innovation to Great-Power Competition". Available at: https://warontherocks.com/2021/01/making-friends-in-maker-spaces-from-grassroots-innovation-to-great-power-competition/

Collaboration and Partnership:

The project was demonstrated to the 1st Special Forces Group (1SFG) Technical and Information Support Company (TISC) leadership in March of 2021. Moving forward, the project will seek to work more closely with all SFG TISCS as collaborators.

Transition:

Adapting the current security force assistance activities of American advisors — especially special operations forces — to foster and empower partner forces would be a potent mechanism to foster such tailored solutions. Further, these home-grown capabilities would establish crucial "buy in" from the end-user while also building stronger relationships with U.S. partners. The technology is also readily available. The commercial market is often leaping ahead of the defense sector in producing ready-made tools for many of the functions that smaller militaries require. From hardware to software, the private sector keeps refining, miniaturizing, and productizing the components that can be modified or repurposed for security applications. Unmanned systems, such as Romulo's prototype is the perfect class of projects as they are universally desired, there is growing competition in this space by GPC competitors, and there is a rich COTS landscape to draw from

Romulo's work demonstrates the viability of designing and building a prototype to basic military specifications by a user who had no technical expertise. He relied almost solely on open-source information, the RoboDojo, and minimal funding. This experience shows that a solution to a capability gap need not be expensive and exquisite. The solution might rather be low-cost and bottom-up, as was the case here. Not only did the Force Recon Marines find a solution to their own problem, but the method of such a solution can "trickle-up" to the broader military organization by sparking wider innovation networks and activity across the Armed Forces of the Philippines.

Given this, what would successful adoption and integration look like? We think it would work in three inter-locking components.

Doctrinal Adoption

The first goal would be to work with the most relevant elements of the U.S. Joint Force in regards to Security Force Assistance. These reside within the US Special Operations Forces (USSOF) community. US Army Civil Affairs is an especially attractive partner here. We have, through our Defense Analysis students, direct access to Civil Affairs leadership.

Synchronizing with Relevant Lines of Effort

Working with partner forces spans many existing lines of effort and funding streams across the inter-agency. These include Building Partner Capacity (BPC) activities, Security Force Assistance (SFA), Foreign Internal Defense (FID), as well as foreign

military sales and various Department of State (DoS) efforts. Research and engagement must be done to identify, coordinate with, or at least deconflict with all such relevant efforts.

Leveraging International Professional Military Education Students

The Naval Postgraduate School is a perfect place to host (or at least participate in) many of these projects. Programs such as the Regional Defense Fellowship Program (RDFP), which funds students from many partner nations to NPS and other US professional military education (PME) institutions has already expressed interest in coordinating its selection and support of partner force students with grassroots innovation projects. This would build on an existing relationship and funding source, as both MAJ Dimayuga and COL Jadloc were funded to attend NPS though the RDFP program.

B. Counter Aerial UxS Munition Delivery System

Participants

- Principal Investigator (PI): Christopher Brophy cmbrophy@nps.edu
- Co-PIs:
  Joshua Codoni <joshua.codoni@nps.edu>
- Students:
  LT Kyle Decker (591) , LT Allison Adamos (570), and LT Nathan Stuffle (366/591)

Major Goals

A growing problem facing national security revolves around inexpensive, easily manufactured drones. Sophisticated software can link drones into swarms and inflict heavy damage on the United States and her allies' assets, while rudimentary drones could also be used by terrorists to strike civilians from afar. The current research program focuses on using low-cost and readily available commercial off the shelf (COTS) components to develop a rapid-response solid rocket motor payload delivery vehicle capable of navigation to a pre-defined "handoff" point in space. At the "handoff" condition, the payload delivery vehicle releases gravity-fed guided submunitions, which use a bird-of-prey approach, to engage and disable detected unmanned aerial system threats with a non-lethal "kill" mechanism, such as entanglement. The benefits of this approach include using many cheap COTS components intended for amateur rocketry and hobbyist robotics systems, as well as additive manufacturing techniques to integrate a low-cost platform that is a more symmetrical response to aerial unmanned system swarm threats. The greatest challenges include integrating many COTS components that were intended to function in various other environments into a single, reliable, and capable tactical system. These challenges involve workforce development and training through supporting DOD Officer's Master's Thesis work in many areas of interest, including propulsion; aerodynamics; guidance, navigation, and control; systems integration; and programming (GNC, neural networks for threat detection. The system also utilizes reliable and proven technology in the form of a solid rocket motor booster, which has a plethora of benefits including simplicity, storability, and rapid-response capabilities.

Accomplishments:

The majority of the research in CY21 focused on vehicle development in the area of guidance and control as well as developing and maturing the avionic bay of the system. Key accomplishments are best described in the theses by LT Decker and LT Adamos and are summarized below.

- Four test flights were performed up to altitudes of 6000 feet.
- Improved understanding of inherent vehicle roll damping coefficients and implemented an effective vehicle orientation and roll control for roll-to-pitch plane operation.

- 6 DOF model of flight system developed
- Designed and flight tested a vehicle (sled) separation mechanism capable of separation at higher flight Mach numbers and aerodynamic loads.
- Determined the use of parachute decelerators will not be sufficient for required camera view due to uncontrollable rotation and swing motion on decent. This activity has resulted in the pursuit of grid fin breaking and stabilization after sled separation.
- A standard architecture for the avionics bay was developed based upon cube sat designs. This has greatly improved connectivity and reliability during the launch and flight processes.
- Implemented and verified a flight telemetry system for transmission of critical flight parameters to ground station during tests.
- Developed a protocol and process to simulate the avionics bay to the expected vibration spectrum and accelerations during flight such that the hardware and connections can be verified before flight.

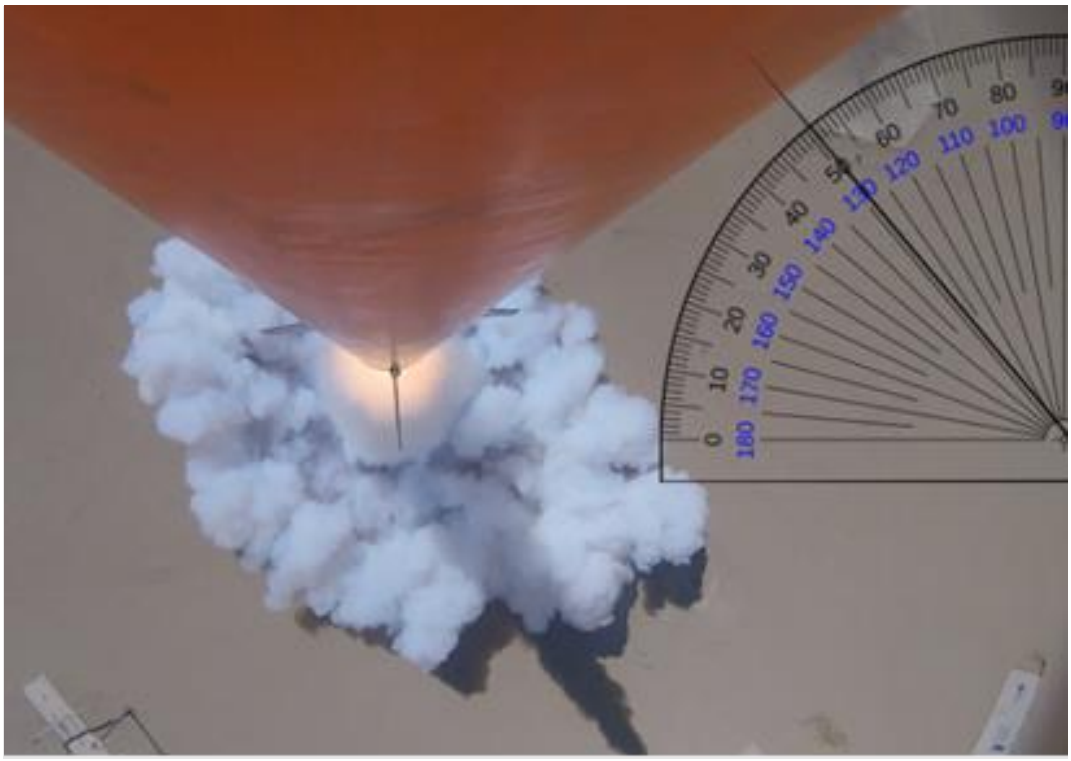

Figure 1: Aft view from rocket tracking roll to heading and subsequent roll cancellation.

Figure 2: Rapid-response vehicle on the launch rail prior to launch with the team (left to right): Professor Josh Codoni, Professor Chris Brophy, LT Kyle Decker, Alexis Thoeny, LT Allison Adamos.

Education:

- Adamos, A. *Design, Development, and Flight Testing of a Modular Avionics and Vehicle Monitoring System*. Naval Postgraduate School, 2021.
- Decker, K. *System Design and Integration of a Rapid Response Payload Delivery Vehicle Using Commercial-Off-The-Shelf Components.* Naval Postgraduate School, 2021.
- Hill, T. *Implementation of Canard Control and Grid-Fin Decelerators on a Rapid Response Payload Delivery Vehicle.* Naval Postgraduate School, Exp. Dec 2022.
- Sherenco, A. Communication, Guidance, and Control of Deployed Submunitions. Naval Postgraduate School, Exp. Dec 2022.
- ME4704 Tactical Missile Design

Dissemination:

At this time, no public dissemination of this work has occurred, and presentations have been limited to thesis briefs and presentations to visitors who share an interest in this technology. Due to recent successes, it is expected that this work will be presented at the next AIAA Aviation conference pending any approval processes that need to occur.

Collaboration and Partnership:

Discussions have occurred with other departments, but only in a precursory manner. The greatest collaborative interaction has been with Dr. Carson Vogt at NPS who has been involved with the programming of the Arduino and Raspberry Pi units as well as the image processing discussions. He expects to continue his role into FY22 and work closely with the current student associated with the guided submunition design.

Transition:

A proposal was submitted to US TRANSCOM that would have involved using the primary vehicle for a payload delivery system versus the delivery of the submunitions. Unfortunately, this proposal was not successful even though it was well reviewed.

We expect to approach both ONR Code 35 again this year to determine if funding could be made available in FY23 to increase the level of activity related to the counter-swarm goals. We also expect to contact the Strategic Concepts Office to determine if they have an interest in continuing the development and maturation of the primary vehicle for the rapid-deployment aspects of the system which would include the use of adaptive optimized guidance.

C. Ethical Control of Unmanned Systems: Repeatable Mission Evaluation Through Unmanned Systems Data Strategy for UMAA/Rail

Participants

- Principal Investigator (PI): Dr. Don Brutzman, NPS Information Sciences Department <brutzman@nps.edu>
- Co-PI: Dr. Curtis Blais, NPS MOVES Institute, Computer Science Department
- Other Participants:
  - Kristen Fletcher, NPS Energy Academic Group
  - Mr. Terry Norbraten, NPS MOVES Institute, Computer Science Department
- Students: None.

Major Goals

Building best-practice workflows for data and metadata from unmanned systems can leverage both field experimentation (FX) and simulation to support archival data re-use and repeatable analysis. Although many components can be found today, the picture is incomplete. Missing capabilities include:

- Regularization of data-collection workflows by operators of unmanned systems.
- Ability to parse and formally define collected information so that it is re-readable and re-usable.
- Ability to replay streams and check parameter results for unit-test assessment.

In this CRUSER 2021 project, we addressed these missing capabilities through several parallel interrelated activities: (1) formalizing data representations of robotic missions, with particular focus on characterization of ethical constraints for specification and execution of those missions; (2) legal review to ensure findings were consistent with current law and policy related to autonomous systems.; and (3) instantiation of an end-to-end data processing chain to capture live unmanned system data for conversion to broadly usable formats. This report summarizes how utilization
of the Data Format Description Language (DFDL) in combination with authoritative schemas for data recording can support these missing capabilities.
The project further investigated, documented, and demonstrated how such capabilities fit within the larger framework, namely an Unmanned Systems Data Strategy for Field Experimentation (FX), modeling and simulation (M&S), live, virtual, and constructive (LVC) Interoperability, and Archival Reuse for Analysis. While addressing the need for broad capabilities for unmanned system testing, this work has direct and critical application to testing of ethical control over unmanned systems. This area of study provides context for technical considerations that need to be addressed to enable human commander/operator control over unmanned systems.

This work is part of an ongoing effort to dismantle stove-piped systems so that open, transparent data can flow freely between systems that previously could not communicate with each other. Using Apache's open-source DFDL we demonstrated the ability to

capture and transform unmanned aerial system (UAS) telemetry and other wirelessly transmitted data into human readable formats and other binary forms enabling cross-linked communications between these systems. Figure 1 illustrates this overall data processing pipeline instantiated for a specific system application.

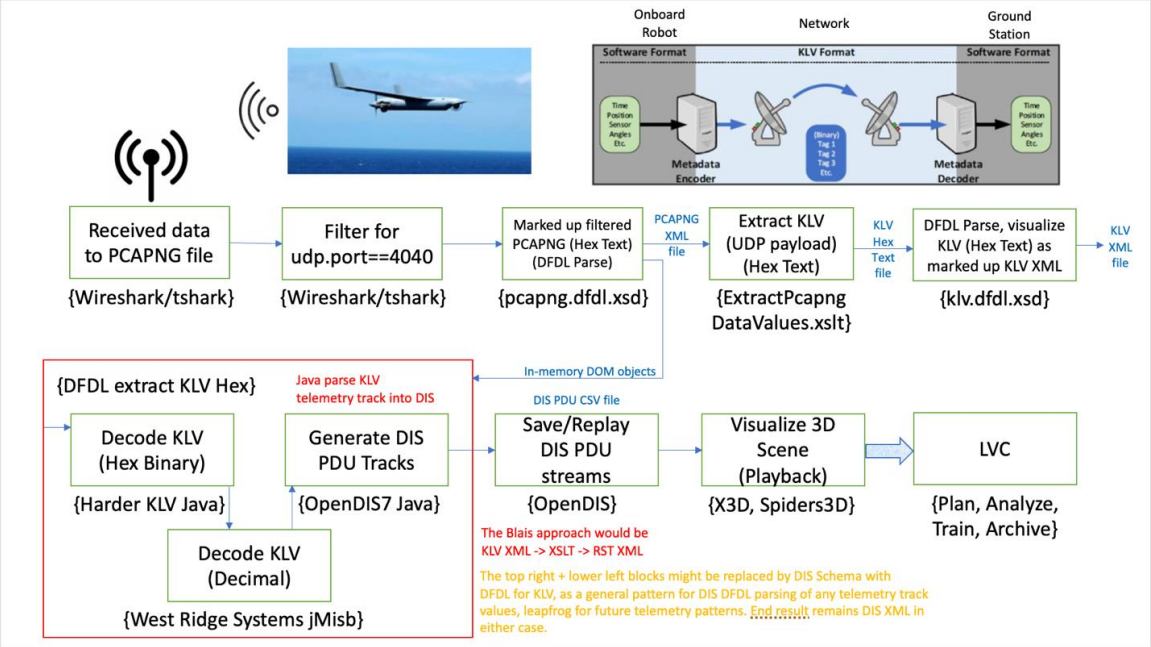

Figure 3: Graphical Representation for the Process of Capturing UAS Local Set Data and Transforming into Other Usable Formats

This process is accomplished using all open source, open standards off-the-shelf tools that support unencumbered business friendly usages via open licensing.

Accomplishments:

With respect to formalization of mission specifications for ethical control of unmanned systems, the project advanced the state of practice in the following areas:

- Define MEO from concepts, properties, relationships using Protégé tool.
- Create full set of canonical missions in AVCL (XML).
- Determine exemplar mappings for AVCL primitives to Turtle for RDF/OWL.
- Write conversion stylesheet AvclToMEO.xslt for full expressiveness.
- Convert all AVCL missions to corresponding triples.
- Confirm AVCL MEO, missions validate satisfactorily using Protégé, ARQ.
- Automate build process as suite of repeatable unit-test queries (log).
- SPARQL queries to test AVCL mission representations in Turtle.
- Write SPARQL metaqueries to test, document MEO ontology relationships.
- Add Shapes Constraint Language (SHACL) statements for mission validation.
- Show how linking various ontologies (mission specification, mission data stream, ethics, policies, provenance) contributes to greater capability in information query and automated reasoning.

- Contributed to development of the IEEE P7007 Ontological Standard for Ethically Driven Robotic and Automation Systems, published November 2021.

With respect to review of ethical and legal policies, the project investigated the following areas:

- Priority Legal and Policy Issues of Unmanned Systems (e.g., in international waters and areas of overlapping jurisdictions): maritime boundaries, protected areas, federal laws relating to such topics as Clean Water Act).
- Analysis of UxS Legal Questions (continuing in 2022).

Key findings in this area include:

- Rapidly-evolving technology challenges law as it lags behind; having lawyers, policy makers and ethicists involved in the design & operation stages can help fill these gaps.
- Laws differ depending on the environment in which the system is operating and the level of autonomy present.
- The need to understand environmental and climate considerations is increasing; we'll include that in our 2022 legal project. We are slated to present at a spring CRUSER meeting on initial findings.

With respect to development of the data processing pipeline, the project advanced the state of practice in the following areas:

- Obtained the data stream (wirelessly transmitted UAS data captured into PCAP Next Generation (PCAPNG) format) from a Joint Interagency Field Experimentation (JIFX) event.
- Transformation of MPEG-2 Transport container wireless data capture in PCAPNG format to human readable and other binary formats via Apache DFDL.
- Extraction and transformation of Key Length Value (KLV) Local Sets (LS) embedded within the MPEG-2 Transport container into human readable and other binary formats via Apache DFDL.
- Decoding of UAS KLV, then populating Distributed Interactive Simulation Protocol Data Units (PDUs) for re-streaming, thereby enabling mission playback in 3D simulation environments via iHarder KLV, West Ridge Systems jMisb, OpenDIS, and X3D.
- Mission playback, analysis, archiving and potential injection of decoded data streams into LVC environments

Additional project information is available at Data Strategy for Unmanned Systems - Network Optional Warfare - NPS Wiki and Ethical Control of Unmanned Systems - Network Optional Warfare - NPS Wiki.

Education:

- The data strategy and data processing methodology was presented in the MOVES MV3500 course as an illustration of needed data transformations from real-world data to virtual environments enabling improved mission analysis, mission replay, and mission experimentation.

Dissemination:

- AI and Laws of War Workshop – through The Technical Cooperation Program (TTCP) (described below), Ms. Fletcher was co-lead on the workshop, hosted by the University of Edinburgh, and involving interdisciplinary colleagues from 5 nations. Ms. Fletcher shared legal findings through discussion and case studies at the workshop.
- Mr. Mike Beckerle, Principal Engineer for OWL Cyber Defense and member of the Apache DFDL Team.
- Presentations in CRUSER webinars on the data strategy and project accomplishments.

Collaboration and Partnership:

- The Technical Cooperation Program (TTCP) – Through the Artificial Intelligence Strategic Challenge, PI Fletcher participated in the Law and Ethics Theme Team with colleagues from the UK, Canada, Australia and New Zealand. This work was funded in part by OUSD(R&E).
- Raytheon Technologies – ongoing research and development of ethical control of unmanned systems through Cooperative Research and Development Agreement (CRADA) tasking.
- Consortium for Robotics and Unmanned System Education and Research (CRUSER) – interaction with ScanEagle JIFX experimentation team.

Transition:

- Support in 2022 is expected for the TTCP Artificial Intelligence Strategic Challenge and participation in the Law and Ethics Theme Team.
- Prepared and submitted a 2022 CRUSER proposal for transition of this research and development to other organizations.
- Ongoing discussions with the Joint Artificial Intelligence Center (JAIC), Commander Operational Test and Evaluation Force (COMOPTEVFOR), and PMS 406 Unmanned Maritime Autonomy Architecture (UMAA) / Rapid Autonomy Integration Lab (RAIL).

D. Communication Dynamics of Human-Machine Teams in Context Sensitive Battle-Field Environment

Participants

- Principal Investigator (PI): A. Mustafa Canan <anthony.canan@nps.edu>
- Co-PIs: Mustafa Demir, Ph.D. Arizona State University, Fulton Schools of Engineering
- Students: USMC LTC Scott Humr, Majs Andrew Barton, and Joel Chuprevich

Major Goals

Although HMTs appear to be the ideal way of integrating AI systems into the military decision cycle, the systemic adoption of these AI/ML-based systems requires a robust understanding of the team dynamics beyond the human-human teams. For example, team interaction, especially communication, is typically studied with explicit information gain; however, information gain can take many forms, including verbal and non-verbal communication, which entail implicit information gain. Team communication occurs between team members regardless of their proximity to one another. Team communication has three essential characteristics: (1) team communication is a process representing a collection of team behavior within a specific time frame; (2) team communication is embedded in a rich context and depends on context; and (3) team communication includes most of the interactions among the team members. Since these characteristics are unique to humans, structure and team design that involve, machines cannot be based on these characteristics.

To explicate these characteristics, we sought answers for the following research questions:

- What are the limitations of an AI system (machine) that can be accentuated in context-sensitive situations? How do these limitations affect communication and decision in HMTs?
- Since human judgments do not always obey classical logic, would a teammate, which is designed and developed with a CPT framework, bound the human intuition?
- Does frequent communication with machines, e.g., in the form of categorization, bound human decision-making and make it deterministic?

Accomplishments:

Although accomplishments are difficult to quantify, the positive and constructive feedback we received on our manuscripts has been encouraging. Specifically, our findings indicate that AI/ML-based systems limitations can complicate team structure. We have identified crucial differences between teamwork and taskwork that are concomitant to the communication among teammates. We developed a probabilistic model to study the relative information gain; we identified dynamic implications of communication to the decision quality and agile decision-making in teams. The model is a probabilistic model that elucidates the differences between human-human information exchange and human-machine interaction. We identified the communication-related differences between teamwork and taskwork. We optimized communication frequency by analyzing experimental data. The results show that for 3 hours mission, team

performance is maximized if the team members communicate 39 times; if it exceeds 41, team performance significantly drops. We identified contextual dependency in communication with incompatible cognitive event representation. If events are incompatible, a joint frequency distribution cannot be formed; as a result, a machine may not run its algorithm as efficiently as a human. In team dynamics, this can emerge as a significant bottleneck, especially in agile team decision making.

Education:

- Thesis in progress: Communication Dynamics of HMTs: Should we Adopt Machines as Teammates? Majs. Andrew Barton and Joel Chuprevich.
- Dissertation fifth area study: Communication and Trust in socio-technical systems from a system dynamics perspective. LTC Scot Humr

Dissemination:

- Modeling Team Interaction and Interactive Decision-Making in Agile Human-Machine Teams
- 2021 IEEE 2nd International Conference on Human-Machine Systems (ICHMS), 1-6 (peer-reviewed conference)
- Addressing Two Central Issues of Team Interaction Dynamics: the Whole is Greater than the Sum of Its Parts. 12th International Conference on Applied Human Factors and Ergonomics (AHFE 2021), New York, NY, USA (peer-reviewed conference)
- A probabilistic perspective on Human-Machine Interaction, HICS 2022 (forthcoming) (peer-reviewed conference)
- A proof concept: Probabilistic Human-Machine Interaction. Submitted to Human-Computer Interaction Journal (under review)

Collaboration and Partnership:

- Arizona State University
- Old Dominion University
- University of Nebraska
- Military Sealift Command

Transition:

- NPS and ASU led the white paper submission to ONR MURI call for competitive proposal submission (#N00014-21-S-F004).
- The white paper was invited to submit a full proposal. The proposal was submitted on September 27th, 2021 (Pending Decision).
- We expanded the collaboration on this work beyond NPS and ASU and started a collaboration with the U.S. Air Force Academy, University of Alabama, University Nebraska, and Old Dominion University.
- The results of this seed project were used to submit a proposal for “Decision Making in Complex Situation with Digital Twin Application.” Military Sealift Command is the sponsor of this project. This is a collaboration between NPS and Old Dominion University. (This project has been funded.)

E. Developing Operational Planning Simulations for Defense Against Attacking Drone Swarms

Participants

- Principal Investigator (PI): Abe Clark <abe.clark@nps.edu>
- Co-PIs: Isaac Kaminer <kaminer@nps.edu>
- Students: Maj Michael Wish, USMC

Major Goals

Previous work from this collaboration involved development of computer simulations that modeled adversarial drone swarm engagements and developed optimal tactics to accomplish a given task. These simulations included modeling of the dynamics of each agent, modeling of mutual attrition between enemy drones, and optimal control techniques that could, in principle, automatically generate the best trajectories. The output of these simulations would be, e.g., the best trajectories for defenders to fly in order to defeat an attacking swarm and protect some high-value asset. Our previous work demonstrated proof of principle for this technique and motivated it as a useful tool. However, the simulations were only useful as an abstract research tool.

The overarching goal of this project was to move this research into a form that could be most relevant to mission planners and other entities throughout the DoD. To accomplish this, we proposed to work with Marines at Ground-Based Air Defense (GBAD), who had developed electronic, anti-drone weapons, to develop a user-friendly simulation platform that could be delivered to them. The simulation platform would allow users to specify the positions and trajectories of attacking drones, guess a defense strategy, allow the computer to automatically optimize defense strategies, and accurately model the anti-drone weapons systems with (potentially classified or sensitive) parameters that could be put in by the end user. This was accomplished in full, and the PI and Maj Wish will visit with the Marines to demonstrate this product on December 10, 2021. Screenshots from these simulations are shown in the figure below.

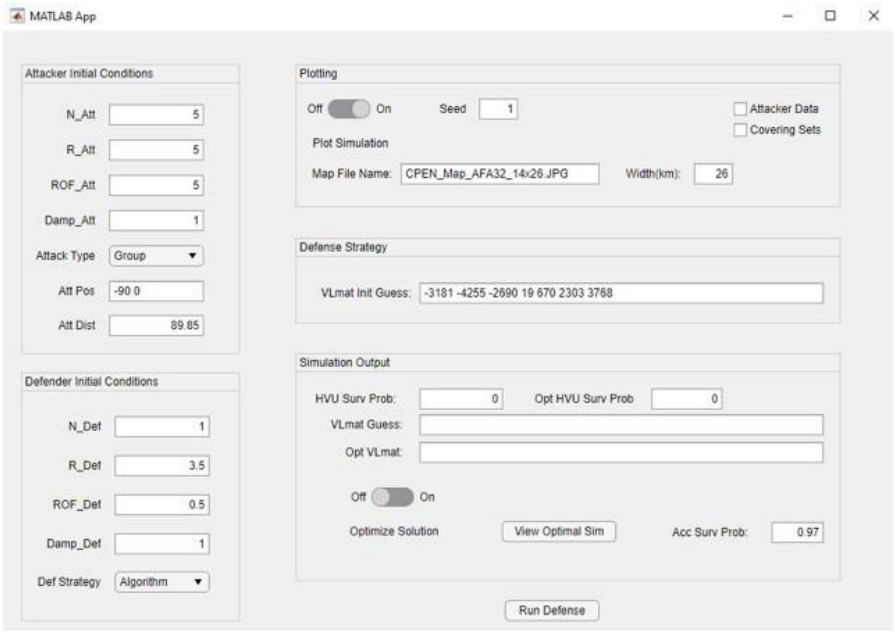

Figure 4: Simulation Screenshot

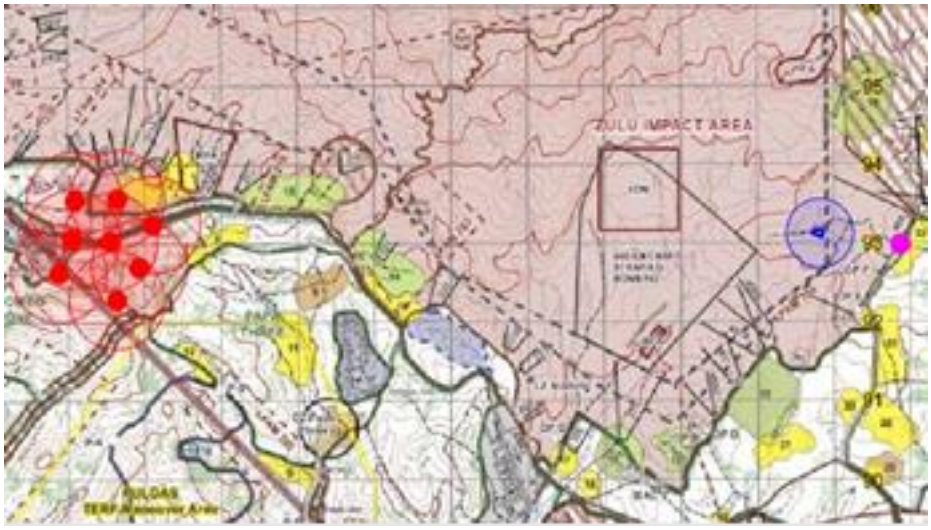

Figure 5: Simulation Screenshot

Accomplishments:

- Research simulations were successfully converted into a form that could be used by Marines at GBAD
- During the course of this main goal, several smaller technical challenges were overcome, including discretizing flight paths in a way that avoided a computationally intractable treatment of the fixed-wing flight constraints.
- These simulations are the basis of potential collaboration with the high-power microwave (HPM) group at NSWC Dahlgren Division. A follow-on proposal will be submitted for FY23.

Education:

- Maj Michael Wish's thesis is directly supporting this project. He is pursuing a dual degree in Physics and Applied Math and is being advised by the PI and the co-PI (although his official math advisor is Wei Kang, who is also a collaborator in this research area).
- A second thesis student, LT Nathan Redder (USN), has recently joined the group and will work on this project as well.

Dissemination:

Tsatsanifos, Clark, Walton, Kaminer, & Gong (2021). Modeling and Control of Large-Scale Adversarial Swarm Engagements. accepted to IEEE CDC 2021 (arXiv:2108.02311).

Walton, Kaminer, Gong, Clark, & Tsatsanifos (2021). Defense Against Adversarial Swarms with Parameter Uncertainty. *submitted to IEEE TNCS (arXiv:2108.04205)*.

Collaboration and Partnership:

We have collaborated directly with the Marine Ground-Based Air Defense (GBAD) unit at PEO-LS. The POCs there are Tom Foddrill (tom.foddrill@usmc.mil) and Mike Wade (michael.wade.ctr@usmc.mil).

We have also begun collaborating with the high-power microwave group at NSWC Dahlgren. The POC there is John Robie (john.w.robie@navy.mil).

Transition:

Our CRUSER-sponsored work was partly responsible for ideas that led to a funded ONR proposal in 2021. Additionally, we are making a trip to NSWC Dahlgren on December 9-10, partly to plan a proposal with the HPM group there. Drones are currently being equipped with HPM weapons, and our modeling tools present a natural way to perform a variety of parameter variation studies.

F. Expediting Swarm System Development with High Fidelity Live/Virtual Modeling and Simulation

Participants

- Principal Investigator (PI):
  - Dr. Duane Davis, Senior Lecturer, Computer Science dtdavi1@nps.edu
- Co-PIs:
  - Dr. Kevin Jones, Associate Professor, Mechanical and Aeronautical Engineering
  - CDR Kathleen Giles, USN, PhD, Assistant Professor, Systems Engineering
- Additional Research Support:
  - Marianna Jones, Faculty Associate Research
  - Katherine Cain, Faculty Associate Education
  - Marina Lesse, Faculty Associate Research
  - Jessica Herman, Professor of Practice
- Students:
  - Robert Hutchens, CHDS
  - Nikolas Carter, CS
  - Peter Pommer, CS

Major Goals

The focus of this research effort was for the Naval Postgraduate School (NPS) Advanced Robotic Systems Engineering Laboratory (ARSENL) to leverage prior experience in aerial swarm operations to develop operator and developer-focused mechanisms supporting rapid development of swarm capabilities and high-level control of swarm missions. ARSENL aimed to explore 1) improvements to their composable swarm behavior framework that demonstrate its support to behavior development and operator oversight of operational missions, 2) approaches to developing accurate physics-based models of swarm vehicles in support of more robust verification and validation, and 3) realistic faster-than-real-time simulation of swarm behaviors as they are developed. Exemplar behaviors were implemented and demonstrated in live-fly experiments conducted at Camp Roberts, CA.

Accomplishments

- ARSENL completed three field experimentation events at Camp Roberts, CA: FX47 12-14 May 2021, FX48 8-10 September 2021, and FX49 15-17 November 2021.
- ARSENL accomplished the first research objective by expanding and improving the composable swarm behavior framework. Several new swarm tactics and plays were developed. A number of factors including lost live-fly experimentation opportunities (partially due to Covid restrictions) and a failure to enlist suitable thesis students for the modeling efforts limited progress on the second and third research objectives. Specific accomplishments included the following:
  - During FX47, ARSENL demonstrated their first multi-domain, live-virtual mission with all swarm platforms. Missions included fixed-wing Zephyr

and Penguin UAVs, quadrotor Mosquito Hawks, a Rover UGV, and two virtual Rover UGVs conducting the *Rover Escort* and *Reloading Cued Response* swarm tactics.

- ARSENL developed and demonstrated an *Evade & Rejoin* swarm tactic during FX47. Notionally designed to provide monitoring of a potentially hostile target, this tactic directs the swarm to converge on a point (e.g., the contact) and evasively diverge after a specified time interval. The converge and diverge maneuver sequence repeats indefinitely. This tactic includes two new swarm plays: *Converge* and *Disperse*.
- ARSENL demonstrated the new *Offensive Sweep* and *Defensive Sweep* swarm tactics using five Mosquito Hawks during FX47. The *Offensive Sweep* tactic is designed to conduct a coordinated sweep over an objective area. The vehicles take up equidistant positions along an arc outside of the objective area and commence a parallel transit over the area once all of the vehicles are in position. The maneuver is defined as a range from the center of the target area, minimum and maximum sector angles, and sweep direction. This tactic is composed of two new plays: *Offensive Cordon* and *Linear Sweep*. The *Defensive Sweep* tactic works similarly except that the vehicles take up positions along an arc at a specified distance from a defended point and conduct the linear outward from the center of the arc's circle. The defensive sweep tactic utilizes the *Defensive Cordon* and *Linear Sweep* plays.
- During FX48, ARSENL demonstrated improvements to existing tactics and plays. In particular, updates to previously documented search/pounce tactics (static role assignment, dynamic assignment with immediate role changes, and dynamic assignment with delayed role changes) were demonstrated. Improvements focused on the underlying task assignment auction implementations and data capture to quantify search and contact engagement effectiveness. Unfortunately, experimentation beyond demonstration of these incremental updates was hampered by ground-to-air communications difficulties.
- During FX49, ARSENL validated a one-hop forwarding protocol for ground-to-air communications that alleviated communication difficulties observed during FX48. In addition, experiments were conducted with new Mosquito Hawk antenna configurations were conducted.
- Also during FX49, ARSENL successfully collected in-flight data in support of future publication for the following tactics and fleet configurations:

Tactic or Play	4 Zephyrs + 4 Mosquito Hawks	3 Zephyrs + 3 Mosquito Hawks	2 Zephyrs + 2 Mosquito Hawks
Prim Search	√	√	√
Swarm Search	√	√	√

Search & Pounce Static	√	√	√
Search & Pounce Immediate	√	√	√
Search & Pounce Delayed	√	√	√

Figure 6: ARSENL In-Flight Data Collection

Education

- The Next Generation of Wildland Firefighting: Using UAV Swarms for Initial Attack *(in work)*
- Thesis: Design and Implementation of a Distributed Ledger to Support Data Survivability in an Unmanned Multi-Vehicle System (received Outstanding Thesis recognition)
- Thesis: Design and Verification of a Distributed Ledger Protocol for Distributed Autonomous Systems using Monterey Phoenix (received Outstanding Thesis recognition)
- CS4313 (Advanced Military Robotics) multi-robot system material was updated based on the results of this work.

Dissemination

- Giles, K. B., Davis, D. T., Jones, K. D., & Jones, M. J. (2021, June). Expanding domains for multi-vehicle unmanned systems. In *2021 International Conference on Unmanned Aircraft Systems (ICUAS)* (pp. 1400-1409). IEEE.
- Carter, N., Pommer, P., Davis, D., & Irvine, C. (2021, September). Increasing log availability in unmanned vehicle systems, In *2021 National Cyber Summit (NCS21) Research Track*. Springer International Publishing.

Collaboration and Partnership

A Small Business Technology Transfer (STTR) in collaboration with Stottler Henke Associates, Inc. in support of a phase I proposal for DARPA's Topology-Agnostic Resource Management and Control (TARMAC) program (HR001121S0007-25) has been submitted and is currently pending. A second STTR was submitted in collaboration with Orbit Logic for Artificial Intelligence and Machine Learning-Based Autonomous Mission Planning for ISR Missions was submitted to NAVAIR but not selected.

G. Priority Legal and Policy Issues of UxS

Participants

- Principal Investigator (PI):
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- Co-PIs:
  Eric Hahn / ehahn1@nps.edu
  Marina Lesse / marina.lesse@nps.edu
- Students:
  LT Austin Taylor, Systems Engineering, NPS
  LT Janice Mallery, Systems Engineering, NPS
  Philip DeCocco, Political Science, Marquette University

Major Goals

The project objectives were to identify priority legal and policy questions, research the most pressing questions affecting the design and operation of UxS, and provide a more thorough understanding of the considerations and requirements under multiple legal regimes and the evolving web of international governance related to UxS and use of these systems by the Navy and DoD. Research included national and international laws that apply to these systems, legal and policy gaps that do or potentially can hinder use, and legal and ethical challenges associated with the spectrum of autonomy. Project goals also included furthering efforts to ensure that DoD lawfully operates UxS in the U.S. and across the globe and contributing to the body of law and policy research relevant to design and use of cutting-edge technology in UxS.

Researchers focused on law and policy research to build on the literature that has identified legal and policy gaps. Researchers collaborated with public and private sector partners to ensure that the subtleties and unanswered questions in U.S., allied states, and international laws were considered. In addition, researchers analyzed caselaw, statutes, treaties and official policies, such as DoD and Navy directives and instructions.

Accomplishments:

- Legal Priorities Report – The primary outcome is a report detailing the legal landscape for AS under U.S. and international law. The report lays out two scenarios that detail laws that apply to autonomous systems as they operate in different maritime zones including international waters, EEZs and overlapping jurisdictions U.S. waters.
- Key findings include:
  - Rapidly-evolving technology challenges law – whether statutory, customary, policy, etc.
  - Law and policy often will lag; a more coordinated approach can fill these gaps quicker.
  - Laws and policies are drafted generally to apply to AS but may differ depending on the environment in which they operate and the level of autonomy present.
  - In the international realm, law and policies varied or were not yet established.
- Collaboration revealed additional questions and policy concerns including specific questions from Navy attorneys that arise in Navy and DoD work, the need to address potential environmental hazards resulting from expendable UxS and international UxS legal questions arising in the classified environment. While it is unlikely each question can be answered definitively, analysis can inform those setting policy and those designing and operating UxS and offer a better understanding of applicable law and potential consequences. These issues will be pursued in Year 2.

Education:

- Capstone Project under the Human-Autonomy Teaming Project is underway. Legal research has directly contributed to the team's design work and planned operations.
- Summer intern conducted initial research on definitions of AS and conducted research and analysis for Scenario 1 and laws applying in various maritime zones.

Dissemination:

- Fletcher, Invited Presentation, University of Alabama Huntsville (November 2021)
- Fletcher, Briefing, CRUSER Monthly Meeting (March 2021)
- DeCocco, Intern Briefings, Energy Academic Group (July/August 2021)
- DeCocco, Report, *Unmanned and Autonomous Systems: Navigating Today's Legal Atmosphere* (August 2021)
- Fletcher has a paper underway on law and ethics with UAH Professor Nick Jones. This paper will be submitted to interdisciplinary journals.
- Fletcher and Lesse have a paper underway on environmental implications of expendable autonomous systems. The Year 2 CRUSER project will contribute to this paper.
- Fletcher, AI and Laws of War Workshop – Through the TTCP (described below), Fletcher was the co-lead on the workshop, hosted by the University of Edinburgh, and involving interdisciplinary colleagues from 5 nations. Fletcher shared legal findings through discussion and case studies at the workshop.

Collaboration and Partnership:

- University of Alabama Huntsville – Through the CRUSER-funded Human-Autonomy Teaming project, legal research has been shared with faculty and students at the University of Alabama Huntsville and public and private sector partners including Boeing, NASA and Dynetics.
- The Technical Cooperation Program (TTCP) – Through the Artificial Intelligence Strategic Challenge, PI Fletcher participated in the Law and Ethics Theme Team with colleagues from the UK, Canada, Australia and New Zealand. This work was funded in part by OUSD(R&E)

Transition:

- CRUSER 2022 Project: Advancing Clarity: Analysis of UxS Legal Questions is funded for 2022.
- Two invited white papers are in development for submission to NASA for consideration of legal gaps related to autonomous systems and how to design a system in the absence of legal clarity.
- 2022 support is expected for the TTCP Artificial Intelligence Strategic Challenge and participation in the Law and Ethics Theme Team.
- Future support also will be sought through ONR sponsored research, related funding mechanisms for UxS and artificial intelligence such as DARPA, and the Naval Meteorology & Oceanography Command Office of General Counsel (CNMOC OGC) in the context of Glider Operations Center at the Naval Oceanographic Office (NAVO) and tabletop exercises that include legal issues.

H. Behavior Automation for UxV Networked Control Systems

Participants

- Principal Investigator (PI):
  - Douglas Horner dphorner@nps.edu
- Co-PIs:
  - Ruriko Yoshida, ryoshida@nps.edu
  - Geoffrey Xie, xie@nps.edu
- Students:
  - MAJ Larry Wigington, OR
  - LT(jg) Liu Yixuan
  - LT Timothy Howarth, MAE
  - LT Dan Harter, MAE

Major Goals:

Unmanned Networked Control Systems (UxV NCS) offer a powerful new capability for military forces. They can provide better situational awareness together with the ability to project and protect forces. An important consideration is the ability to retain command and control. While systems may have the ability to be fully autonomous, human control is critical for distributed systems that may have the future ability to deploy weaponry.

To realize this seamless transition between semi-autonomous and autonomous operations, a critical additional component of the UxV NCS autonomy architecture is the ability to remediate between multiple, simultaneously assigned tasks. They must be safely integrated within a hierarchy of tasks that includes system-wide parameters such as communications optimization with individual agent objectives such as obstacle avoidance, path planning, path following and position estimation. The goal of this research was the initial development for a distributed UxV NCS that permits rapid integration of behaviors/tasks for autonomous and semi-autonomous control.

Accomplishments:

- Integration of Human-on-the-Loop (HOTL) control within the hierarchical UxV NCS.
- Development of a Red Cell analytical framework for incorporating operational deception.
- Development of initial behaviors within the hierarchical AI/ML framework.

Education:

- Student theses
    - L. Wigington, “Red cell analysis for mobile networked control systems”, Master’s thesis, Operations Research Department, Naval Postgraduate School, Monterey, CA, 2021.
    - L. Yixuan, “Solving reward-collecting problems UAVs against the stochastic adversary through reinforcement learning and online optimization”, Master’s thesis, Operations Research Department, Naval Postgraduate School, Monterey, CA, 2021.
    - B. Lowry, “Distributed submodular optimization for a UxV networked control system”, Master’s thesis, Mechanical and Aerospace Engineering Department, Naval Postgraduate School, Monterey, CA, 2020.
    - D. Kurt, “Active Terrain Aided Navigation”, Master’s thesis, Electrical Engineering Department, Naval Postgraduate School, Monterey, CA, 2020.
- NPS courses supported by the effort.
    - Introduction to Unmanned Systems (ME3720)
    - Advanced data analysis (OA4106)
    - Statistics for Technical Management (OS3105)
    - Naval Tactical Analysis (OS3680)
    - Joint Campaign Analysis (OA4602)
    - Introductory Computer Networking (CS3502)
    - Robust and Secure Network Design (CS4552)
    - Seminar on Faculty Research Topics (CS4900 2 sections)

Dissemination:

Discussion of the results have been focused on potential initial candidate users. This includes Naval Special Warfare and the Marine Corp - military commands that focus on Naval expeditionary warfare. More generally, publications include the following:

- D. Horner, “NPS CRUSER MTX After Action Report 2017-2020,” Monterey, California. Naval Postgraduate School, 7202.
- L. Wigington, R. Yoshida and D. Horner, “Red Cell Analysis for Mobile Networked Control Systems”, Emerging Technology 2021. . https://cimsec.org/emerging-technologies-week-kicks-off-on-cimsec/
- Y. Liu, R. Yoshida, C. Vogiatzis, and E. Morman, "Solving reward-collecting problems with UAVs: a comparison of online optimization and Q-learning", To appear in Journal of Intelligent & Robotic Systems.

Collaboration and Partnership:

The collaborative research group has briefed the following organizations:

- Bruce Morris, Naval Special Warfare N9 Future Concepts.
- MAJ Ryan Keller, Marine Corp Tactical Systems Support Activity (MCTSSA).
- James Caley, Director for Operational Energy, RDT&E RDA Department of the Navy.
- Nicholas Gizzi, Navy Command and Control Program (PMW 150).

Transition:

The research has resulted in a new 2022 research program funded by the Department of the Navy, RDT&E RDA, Director for Operational Energy. The research, entitled "Opportunities for long dwell/duration group UASII/III UAVs and USVs for Raid Annihilation Capabilities of Current Surface Combatants", leverages the UxV NCS autonomy framework for analyzing the impact of organic unmanned systems to support naval surface craft from the perspective of operational energy and the probability of raid annihilation (Pra).

I. Aqua-Quad Vector Sensor Integration and Participation in Trident Warrior 2021

Participants

- Principal Investigator (PI): Kevin Jones <kdjones@nps.edu>
- Co-PIs:
  Vladimir Dobrokhodov vndobrok@nps.edu

  Paul Leary pleary@nps.edu

  Kevin Smith kbsmith@nps.edu

Major Goals

Primary goals this year included integration of a novel sensor in collaboration with our transition partner (NUWC Keyport), field testing of the Aqua-Quad platform in an ocean environment, and evaluation of the Aqua-Quad/sensor system for realistic mission sets, with participation in high visibility events such as Trident Warrior. Additional goals included optimization of the airframe design for improved survivability and payload modularity, and exploration of the flight envelope with added payload weight and a heavy slung payload. Due to COVID travel constraints, we were unable to prepare in time for participation in TW21. However, a proposal has been submitted to Coastal Trident 2022.

Field experiments were carried out at the test range on Dabob Bay in May and September. The May event included the first test flights with the Aqua-Quad landing on and taking off from water. This was a spectacularly uneventful experience. Both in manual and fully autonomous flights, the system was stable on the water and automatically detected the landing every time. A water takeoff is depicted in Figure 1, filmed by a Parrot ANAFI, courtesy of Eric Silberg from NSWC Carderock.

Figure 7: Aqua-Quad lifting off in Dabob Bay with the slung load still submerged

Knowledge gained in those experiments led to the modifications in the design and packaging of some components. Flights with the slung load were also uneventful. If the period of the pendulum is below the natural control frequency of the copter, there are really no concerns other than tether management on dry land. Initial data from the novel sensor payload are extremely promising but will require some additional work for thermal management and robustness.

Accomplishments:

- Refined the airframe design for improved stiffness, environmental hardening and flight handling. The airframe is readily produced in a makerspace with moderate 3D printing and desktop CNC machining capabilities. Other system modifications resolved issues with:
    - Motor-desyncing under heavy loads – software fix.
    - Destructive electrolysis on exposed high-power electronics – switched from conformal coating to fully potted parts.
    - Weak yaw authority that is typical of lightly-loaded multi-copters – canted motors to provide direct thrust for yaw. Switched to reverse-yaw configuration for improved thrust distribution in cruise flight.
    - Frame flexibility – the carbon fiber (CF) frame supporting the motor arms has a large hole in the middle to allow for the pressure vessel that greatly weakens the structure. Creative use of CF parts and fiber directions greatly improved frame stiffness with no additional weight.
- Achieved flights taking off from and landing on water, both manually piloted and fully autonomous.

- Flights were carried out with all-up-weights between 2.4 kg (airframe+battery) and 3.6kg (+1.2 kg payload, split between internal and external – slung load).
- Flight tests performed with slung payloads, hanging between 30 and 45m below the airframe on a thin tether. Tests included flights from land and sea at flight speeds up to 28 knots. Tests included flights with a light payload on the end of the tether where the tether trailed very far behind the airframe, to very heavy payloads where the payload hung almost directly below the airframe.
- Integration and testing of a novel undersea sensing technology.

Education:

- Dillard, C. H., 2014, "Energy-Efficient Underwater Surveillance by Means of Hybrid Aquacopters," Master's thesis, Naval Postgraduate School, Monterey, CA, USA.
- Casey, L, 2015, "Continuous Acoustic Sensing with an Unmanned Aerial Vehicle System for Anti-Submarine Warfare in a High-Threat Area," Master's thesis, Naval Postgraduate School, Monterey, CA, USA.
- Yang, Sean, 2020, "Study of the Power Required for Flight of the Aqua-Quad (Solar-Powered Quad-Rotor Unmanned Aerial System," Master's thesis, Naval Postgraduate School, Monterey, CA, USA.
- Lim, Gabriel, 2020, "Modeling of the Aqua-Quad Solar Power Generation System," Master's thesis, Naval Postgraduate School, Monterey, CA, USA.

Dissemination:

Recent developments are sensitive and have not been published in the public. Historical publications supported by CRUSER include:

- Jones, K., Dobrokhodov, V., and Dillard, C., 2016, "Aqua-Quad - Solar Powered, Long Endurance, Hybrid Mobile Vehicle for Persistent Surface and Underwater Reconnaissance, Part I - Platform Design," OCEANS 2016 MTS/IEEE Monterey, pp. 1–10.
- Dobrokhodov, V.N., Jones, K.D., Dillard, C., & Kaminer, I.I., 2016, "Aqua-Quad - solar powered, long endurance, hybrid mobile vehicle for persistent surface and underwater reconnaissance, part II - onboard intelligence," OCEANS 2016 MTS/IEEE Monterey, 1-9.
- Patents: US 9,321,529, US 9,457,900 B1

Collaboration and Partnership:

Naval Undersea Warfare Center, Keyport Division, Mark Paulus and James Richards. NUWC Keyport is a transition partner, developing a novel sensor payload for evaluation on the Aqua-Quad platform. We have submitted a proposal for Trident Coastal 2022. We are also exploring potential opportunities with NSWG-8, with a flight experiment planned for mid-December, 2021.

Transition:

The team at NUWC Keyport has expressed an interest in continued experimentation and potentially obtaining a few Aqua-Quad systems for testing on their end. We have also been exploring potential collaboration with Naval Special Warfare Group 8 for additional payload and mission opportunities with Aqua-Quad and derivative systems.

J. Hybrid USV Attacks for Counter-Swarm Experimentation

The following report is Distribution Statement A: Approved for public release. However, the subject CRUSER Seed Research Project is Distribution Statement D: Distribution authorized to Department of Defense and U.S. DoD contractors only. Project details can be provided on request in a Distribution D Appendix.

Participants

- Principal Investigator (PI): Sean Kragelund <spkragel@nps.edu>
- Co-PIs: Isaac Kaminer <kaminer@nps.edu>
- Students:

    LT Samuel Royster (570)

    LT Alexander Fedorovich (570)

Major Goals

The objective of this research was to develop and field-test tactics for a "hybrid" attacking swarm composed of identical unmanned surface vessels (USVs) but imbued with different capabilities. Experimental swarm algorithms were developed in simulation and field-tested in force vs. force engagements. Our technical approach integrated an NPS-developed software architecture with various swarming and coordinated path following (CPF) algorithms onto a subset of agents in an existing USV swarm. Although indistinguishable from other boats in the swarm, the NPS "subswarm" proved capable of executing unpredictable trajectories that deviated from prevailing swarm behavior. The operational objective was to influence maritime swarm defense tactics by stress testing existing defensive systems through more effective swarm attacks.

The effort involved NPS students in several ways. First, LT Royster contributed to modeling, simulation, and experimental system identification of the USV platforms used for this project. A well-known swarm algorithm for goal-seeking and formation-keeping was adapted to suit these platforms' non-holonomic dynamics, and researchers implemented this algorithm onto several USVs using the Robot Operating System (ROS). Using this algorithm as a baseline, students in the "Cooperative Control of Multiple Autonomous Vehicles" used ROS and the Gazebo physics-based virtual environment to develop and test different swarm attack tactics. In simulation, LT Royster and LT Fedorovich demonstrated algorithms that enabled a swarm of USVs to navigate through a harbor choke point and attack a target of interest. Extensive field testing on Lake Del Monte validated this approach for a swarm of three USVs. In addition, we developed a method for rapidly cloning the NPS software architecture onto various USV platforms of opportunity, even under austere field conditions.

Accomplishments:

- The simplicity of the baseline swarming algorithm, along with sufficient inner/outer loop separation between the USV autopilot and NPS guidance controllers produced robust performance during force vs. force experimentation.

- Our scheme for cloning and updating software onto a large number of USV agents proved especially effective in the field. Based on Ansible, an open-source information technology (IT) automation engine, custom playbooks were developed for remotely executing several tasks on each USV in our inventory, including:
    - Download NPS autonomy software source code and build executables.
    - Start, stop, or restart autonomy software processes.
    - Specify which software processes should execute on bootup.
    - Reboot backseat driver systems.
    - Set configuration items related to networking and system time, including network time synchronization (used to synchronize the boat's open-loop virtual leader simulations).
- We demonstrated an ability to integrate NPS hybrid swarm capabilities into existing swarm architectures used by other Navy Science and Technology (S&T) partners.
- See Distribution D Appendix for experimental results.

Education:

- ME4902: Directed Advanced Study in Mechanical Engineering: USV Experimental System Identification (1 student)
- ME4823: Cooperative Control of Multiple Autonomous Vehicles (3 students)

Dissemination:

DoD sponsor has requested no external publication of project results. See Distribution D Appendix for experimental results.

Collaboration and Partnership:

This project involved new and potentially significant collaboration with Navy S&T partners. See Distribution D Appendix for details.

Transition:

This project has already secured a commitment for reimbursable support in the form of matching funds for a follow-on CRUSER project in FY22 (see Distribution D proposal for details). In addition, there is potential to transition this project to full reimbursable support within three years.

K. Predictive Failure Analysis for Autonomous Networked Ground Stations

Participants

- Principal Investigator (PI): Jim Newman, jhnewman@nps.edu
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- Students:
  Capt Tim Marczewski, USA, MS SSO (graduated 06/2021)
  LT Stephen Wistner, USN, MS SSO (graduated 06/2021)

Major Goals

Small Satellite ground stations currently rely on reacting to problems rather than anticipating them. This is due to the lack of data autonomously collected on the system's environment and health and the available time small teams have for managing the system's operations. Autonomous data collection through monitoring hardware and machine learning for automated analysis are assets small satellite ground systems can utilize to improve situational awareness and reduce troubleshooting durations.

The research focused on addressing autonomous environmental and situational awareness through two efforts. First, we integrated environmental and health monitoring equipment with the Mobile CubeSat Command and Control (MC3) ground station at NPS to increase the amount of data collected on the system's environment and health. Software was developed to display the data for easier viewing by ground station operators. Second, machine learning algorithms were evaluated and tested on collected data. A solution using Python and K-means++ was implanted for analyzing antenna vibration data generated over the course of multiple satellite passes.

Accomplishments:

- Integrated environmental and health monitoring hardware with the NPS ground station.
- Utilized sensor hardware for ground station data collection.
- Developed software to communicate with collection hardware, store ground station data, and display information regarding real-time and historical ground station health.
- Researched machine learning algorithms to determine a solution for automated analysis. Determined K-means++ provided the best results.
- Tested machine learning algorithm on antenna vibration data. Determined high frequency data collects were necessary from better vibration sensors.

Education:

- T. J. Marczewski, "Machine Learning in Mobile CubeSat Command and Control (MC3) Ground Stations". M.S. thesis, Space Systems Academic Group, Naval Postgraduate School, Monterey, CA, June, 2021. Accessed on: December 9, 2021. [Online]. Available: https://calhoun.nps.edu/handle/10945/67771
- S. Wistner, "Autonomous Assessment of Satellite Ground Station Health". M.S. thesis, Space Systems Academic Group, Naval Postgraduate School, Monterey, CA. [In Process]

Dissemination:

This research was presented at the December 6, 2021 CRUSER monthly meeting.

Collaboration and Partnership:

- The DoD Space provided resources for a proof-of-concept test of this research with the Mobile CubeSat Command and Control (MC3) ground station at NPS. Limited funding was provided for developing plans for integrating this capability into the operational MC3 network. External POC details available on request.

Transition:

We are currently looking to continue this research as a follow-on activity to the initial seed funding provided by CRUSER. Proposals are being developed to expand and proliferate this effort across the other eight operational MC3 ground stations located throughout the country. Additionally, we plan on increasing the variety and quantity of environmental and systems health data. We also intend to make modifications to our machine learning methodologies for improved autonomous analysis of our collected data. Along with the current proposal plan being submitted to MC3's sponsor at DoD Space to continue the integration effort, we are looking to propose this research effort to SDA and NIWC PAC—with whom we have done research in the past.

L. Formation, Implementation, And Verification of Requirements for Human-Autonomy Teaming

Participants

- Principal Investigator (PI):
  - Douglas L. Van Bossuyt <douglas.vanbossuyt@nps.edu>
- Co-PIs:
  - Rob Semmens – NPS
  - Kristen Fletcher – NPS
  - Kristin Weger – UAH
  - Bryan Mesmer – UAH
  - Nathan Tenhundfeld – UAH
  - Nicholas Jones – UAH
- Students:
  - LT Janice Mallery – 580 Curriculum
  - LT Austin Taylor – 580 Curriculum
  - LT William (Aaron) Melton – 580 Curriculum
  - CPT Mehmet Bahadir – 580 Curriculum
  - LT James Dubyoski – 580 Curriculum

Major Goals

The proposed research objective is to identify impacts on autonomous systems (AS) requirements formation and challenges to verifying AS requirements using law, philosophical, psychological, and engineering approaches. Upon successful completion of the research, actionable information to AS engineers and designers will be delivered in the form of a technical report. It is important to the DoD that requirements for AS are formed, implemented, and verified to improve the effectiveness of warfighters and reduce potential risk to the warfighter. Systems engineers currently primarily form requirements based on the needs and desires of the stakeholders, and are generally formed based on rigid policy interpretations and stakeholder needs. AS have inherent uncertainties that may conflict with these policies and needs.

Accomplishments:

- This work provides a "better" way to define Stakeholder Needs
  - No need to "imagine" the future
  - Easily change capabilities, or play with things that haven't been invented yet
  - Drive UX requirements
  - Develop tactics
- Military branches align on what factors are essential to the acceptance and adoption of AS
- System Reliability: Most impact on user reliance and trust in AS – can lead to complete rejection
- Disconnect between end-users and designers
  - Only 29% had been consulted during R&D phase of AS for military use
  - 93% indicated necessity to include end-user in consultation during R&D
- In military AS brings the most benefit to mundane tasks, logistics, UAS

- Interview developed and piloted to follow team progress of requirement development and verification
- Developed virtual environment for research
- 3 Interviews conducted with the first NPS cohort group
- Transcription and Analysis of Interviews and Logs starting January 2022
- Performed 4 seminars with NPS students on the topic related to ethics
- Weekly meetings with UAH capstone students from all fields of ethics, psychology, systems engineering and computer science since August 2021
- Meet with students to discuss ethical considerations in designing requirements for the system.
- Rapidly-evolving technology challenges law – whether statutory, customary, policy, etc.
- Law and policy will often lag. A more coordinated approach can fill these gaps quicker.
- Laws and policies are drafted generally to apply to AS but may differ depending on the environment in which they operate and the level of autonomy present.

Education:

J. Mallery, A. Taylor, W.A. Melton. 580-202 Combat System Capstone Project: Mounted Tracking Launcher (MTL). Masters Capstone Project Final Report. Naval Postgraduate School. Monterey, CA. September 2021

M. Bahadir, J. Dubyoski. Combat Systems Capstone. Masters Capstone Project Final Report. Naval Postgraduate School. Monterey, CA. March 2022

UAH capstone courses in Industrial Systems Engineering (System Analysis and Design), Psychology (Human Research) and Computer Science

Non-CRUSER funded NPS 522 capstone students have been conducting related research including:

- What tasks should be automated
- What tasks should be handed-off between humans and automation

USMA Cadets, and NSIN interns examined how people should learn to understand robot interfaces, as well as how to understand evolving teammates.

NPS capstone courses in Systems Engineering (two cohorts)

Dissemination:

Flynn, M., Smitherman, H., Weger, K., Mesmer, B., Semmens, R., Van Bossuyt, D., Tenhundfeld, N., “Incentive Mechanisms for Acceptance and Adoption of Automated

Systems", Proceedings of the Annual IEEE Systems and Information Engineering Design Symposium (SIEDS) Conference, Virtual, April, 2021

Matsuyama, L., Zimmerman, R., Eaton, C., Weger, K., Mesmer, B., Tenhunfeld, N., Van Bossuyt, D., Semmens, R., "Determinants that are Believed to Influence the Acceptance and Adoption of Mission Critical Autonomous Systems", AIAA SciTech 2021, Virtual, January, 2021

Matsuyama, L., Weger, K., Mesmer, B., Tenhundfeld, N., Van Bossuyt, D., Semmens, R., "Autonomous Systems Adoption Challenges and Requirements Management Solutions", JIFX 20-4 Technology Expo, Online, September 16th, 2020

Zimmerman, R., Matsuyama, L., Weger, K., Mesmer, B., "Insight into the Acceptance and Adoption of Autonomous Systems by Military Personnel", UAH Research Horizons, Virtual, March, 2021

Steele, J., "Transparency about autonomous military systems is critical to acceptance, research says, UAH, December 2020

Fletcher, Invited Presentation, University of Alabama Huntsville (November 2021)

Fletcher, Briefing, CRUSER Monthly Meeting (March 2021)

Papers in review, in process, etc.

Semmens. How to Develop Tactical Judgment.

Semmens, et al, Systems Requirements for Tactical Judgment in Human-Robot Teams.

Weger, K., Matsuyama, L., Zimmerman, R. Mesmer, B., Van Bossuyt, D., & Semmens (submitted 2021). Insight into User Acceptance and Adoption of Autonomous Systems in Mission Critical Environments. International Journal of Human-Computer Interaction

Weger, K., Matsuyama, L., Zimmerman, R. Mesmer, B., Tenhundfeld, N., Van Bossuyt, D., & Semmens (in preparation for 2022). Design and Human Factors Associated with the Acceptance and Adoption of Autonomous Technologies.

Fletcher and Jones are writing an article (for 2022 publication) about the legal and ethical components of autonomous systems, especially in the context of ethical principles adopted by the U.S. and its allies.

Fletcher and Lesse have an article in progress for 2022 publication on U.S. and international environmental laws applicable to expendable AS.

Van Bossuyt, D., et al., Risk Reduction in Autonomous Systems Requirements Generation and Management (for 2022 submission)

Van Bossuyt, D., et al., Combat Systems Capstones: Agile Processes to Fail Fast and Enhance Learning for the Warfighter (for 2022 submission)

Collaboration and Partnership:

University of Alabama Huntsville – Through the CRUSER-funded Human-Autonomy Teaming project, legal research has been shared with faculty and students at the University of Alabama Huntsville and public and private sector partners including Boeing, NASA and Dynetics.

USMA Cadets, and NSIN interns examined how people should learn to understand robot interfaces, as well as how to understand evolving teammates.

Transition:

- CRUSER 2022 Project: Advancing Clarity: Analysis of UxS Legal Questions is funded for 2022.
- Two invited white papers are under development for submission to NASA for consideration of legal gaps related to autonomous systems and how to design a system in the absence of legal clarity.
- Future support also will be sough through ONR sponsored research, related funding mechanisms for UxS and artificial intelligence such as DARPA, and the Naval Meteorology & Oceanography Command Office of General Counsel (CNMOC OGC) in the context of Glider Operations Center at the Naval Oceanographic Office (NAVO) and tabletop exercises that include legal issues.
- CRUSER 2022 Project: What Makes Johnny 5 Alive? Using Diverse Perspectives to Drive Requirements for Human-Robot Teams. Funded for 2022.
- $65k funding for FY21 from NASA Marshall Space Flight Center to support an aspect of continued research
- $200k funding for FY21 from NASA Glenn Space Center to support an aspect of continued research
- OUSD(R&E) ~$20K toward TTCP AI Strategic Challenge Law/Ethics and AI and Laws of War Workshop (Fletcher)
- Army CCDC DAC FY21 ~$50k associated with related autonomous systems environment development

Further transition plans:

- Brief NPS Warfare Chairs on project results
- Brief NWSI
- Brief Army CCDC
- Present work to Defense contractors
- Publish research in the open literature

M. SUAS-Based Environmental Sampling in Support of High Energy Laser Weapon Systems

Participants

- Principal Investigator (PI): Qing Wang <qwang@nps.edu>
- Co-PI: Ryan Yamaguchi <ryamaguc@nps.edu>
- Students: Lt. Melissa JonMoore, 373

Major Goals

This project intends to develop and evaluate atmospheric measurements based on multicopter Small Unmanned Aircraft System (sUAS) in support of high-energy laser weapon system (HELWS) testing and operation. Multicopter sUAS has been broadly used across the Department of Defense. For atmospheric sensing, they have the clear advantage for reducing requirements of large space for takeoff and landing, as well as reducing the requirement for the advanced flying skill level of fixed-wing pilots. However, they also have apparent disadvantages for hosting the same sensors as fixed-wing sUAS, or land/ship-based towers, because of the flow distortion around the airframe and downward prop wash, which modifies the atmospheric turbulence characteristics.

The goals of this research are to integrate a sensor package to obtain optical turbulence from multicopter systems, test and evaluate the impact of prop wash on environmental sampling, especially for near-surface turbulence with low altitude flights, and develop optimized sampling strategies for measuring optical turbulence in the minimally disturbed environment using multicopter sUAS.

Accomplishments:

- Sensor integration development to produce a sensing system for obtaining the structure-function parameter from multicopter sUAS.
- Coordinated with collaborators from the University of Miami and Ohio State University in joint sUAS flight testing using different multicopter systems.
- Tested optical turbulence package on two types of multicopters next to a 10-m tower instrumented with standard sensors for optical turbulence sensing
- Initial data QC in preparation for student thesis work.

Education:

- Lt. Melissa JonMoore will make intensive analyses of the copter- and tower-based dataset as part of her MS thesis work. She is expected to graduate in June 2023.
- Some of the results will be incorporated into course MR4416 (Atmospheric Factors on Electromagnetic and ElectroOptical waveList NPS courses and capstone projects supported by the effort.

Dissemination:

None yet. But plan to present the result in HEL-related conferences in 2022.

Collaboration and Partnership:

We collaborated with the University of Miami (PI: Brian Haus) and Ohio State University (PI: Caglar Yardim) on the copter measurement testing in two separate weeks. The copters used to host the NPS sensor package were properties of and operated by the collaborators. The measurements support their research on satellite wind retrieval (U. Miami) and radio frequency ducting (Ohio State U). The sampling plan were jointly developed. The copters from both universities are different in size, providing the opportunity to test the flow distortion around different size copters, a major bnefit from this collaboration.

Transition:

A proposal to use the system developed from this project to quantify optical turbulence in the coastal zone titled ‘Characterizing Temporal and Spatial Variability of Optical Scintillation’ was submitted to ONR Code 322 Marine Meteorology and Space Program (POC Katherine Mulreany). The proposal was not funded but was recommended to another related project for consideration.

N. Localization Of Unmanned Ground Systems Using the Zero Velocity Update Technique and A 3-D Lidar in The Absence Of GNSS

Participants

- Principal Investigator (PI):
  - Xiaoping Yun, xyun@nps.edu
- Co-PIs:
  James Calusdian, jcalusdi@nps.edu
- Student:
  Matthew G. Caspers, Curriculum 590

Major Goals

The objective of this project was to investigate a new approach of mitigating error growth of inertial navigation systems (INS) for unmanned ground systems. The error growth associated with the strapdown INS rises from two sources: accelerometer measurement noises and transformation of the accelerometer measurements from the sensor coordinates to the inertial coordinates. Through an earlier investigation, it was found that the INS error growth due to accelerometer measurement noises can be mitigated by applying the zero-velocity update (ZUPT) technique for unmanned ground system applications. Based on this finding and the insight gained in the process of the earlier study, the objective of this study was to investigate approaches for combating the second source of INS error growth by using a 3-D Lidar. By combining an INS sensor with a 3-D Lidar sensor in a complementary manner, the goal was to improve the localization accuracy and reduce the computational cost.

Accomplishments:

- A fusion algorithm was developed, which uses a complementary filter for combining the advantages of a 3-D lidar and an IMU sensor to counteract the disadvantages of each alone, and for providing better registration and mapping results at a reduced computational cost.
- A series of laboratory experiments were designed and carried out to establish a base-line performance of an IMU sensor and a 3-D lidar senor when they were used alone individually for localization, and to validate the effectiveness of the fusion algorithm when an IMU sensor and a 3-D lidar sensor were integrated.
- Experimental results indicated that the fusion algorithm was able to provide more accurate and more consistent localization results than the base-line performance.
- Lidar point cloud registration is computationally expensive, which makes it less ideal for real-time applications. By combining an IMU sensor with a 3-D lidar, experimental results showed that the number of point clouds required for registration can be significantly reduced while still retaining successful registration.

Education:

- Matthew G. Caspers, “Robotic Navigation and Mapping in GPS-denied Environments with 3D Lidar and Inertial Navigation Utilizing a Sensor Fusion Algorithm,” MS thesis in Electrical Engineering, Naval Postgraduate School, Monterey, CA, September 2021.

Dissemination:

None.

Collaboration and Partnership:

None.

Transition:

We are continuing the investigation to further improve and refine the fusion algorithm developed during the course of this project. A proposal is under preparation to seek reimbursable support in an effort to bring this new approach of navigation method to deployable mobile platforms.

O. Enhancing C-UAS Capabilities Using A 3D LiDar

Participants

- Principal Investigator (PI): Prof. Oleg Yakimenko, SE, oayakime@nps.edu
- Students: Maj. Konstantinos Paschalidis, SE, konstantinos.paschalidis.gr@nps.edu
- Dr. Pavan Kumar, NRC Postdoc, SE, pavanbn8@gmail.com

Major Goals

To develop the concept and algorithms; prototype; and assess feasibility / performance of a lightweight mobile three-dimensional (3D) 360^0 Light Detection and Ranging (LiDAR) system for detecting, identifying and tracking multiple intruder unmanned aerial systems (UASs) for counter-UAS (c-UAS) applications (see Fig. 1).

Figure 8: Artistic depiction of the LiDAR-based c-UAS system.

Accomplishments:

- This study developed and followed a LiDAR assessment methodology as applied to c-UAS applications, as shown in Fig. 9.

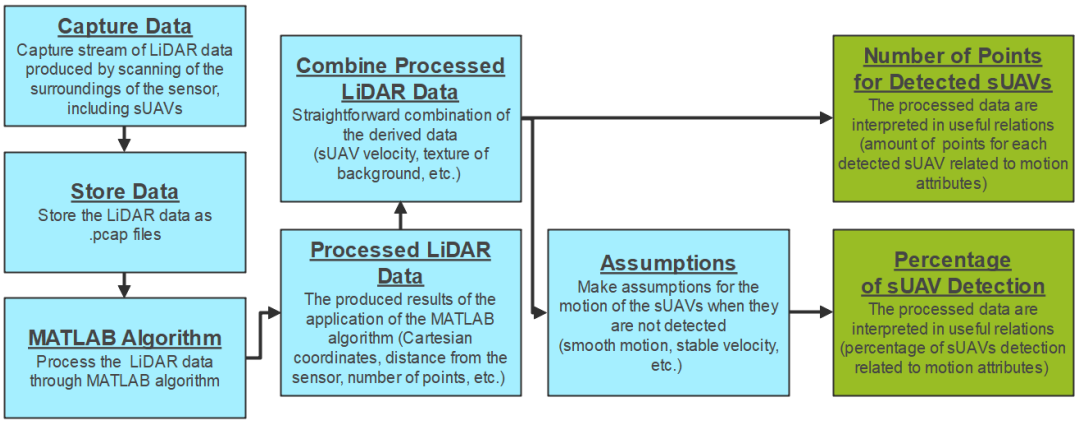

Figure 9: Flow chart of the methodology applied in this research.

- Field experimentation using a Velodyne Puck LiDAR helped to understand the technology (Fig. 10) and learn about its limitations as related to detecting small UAS (sUAS).

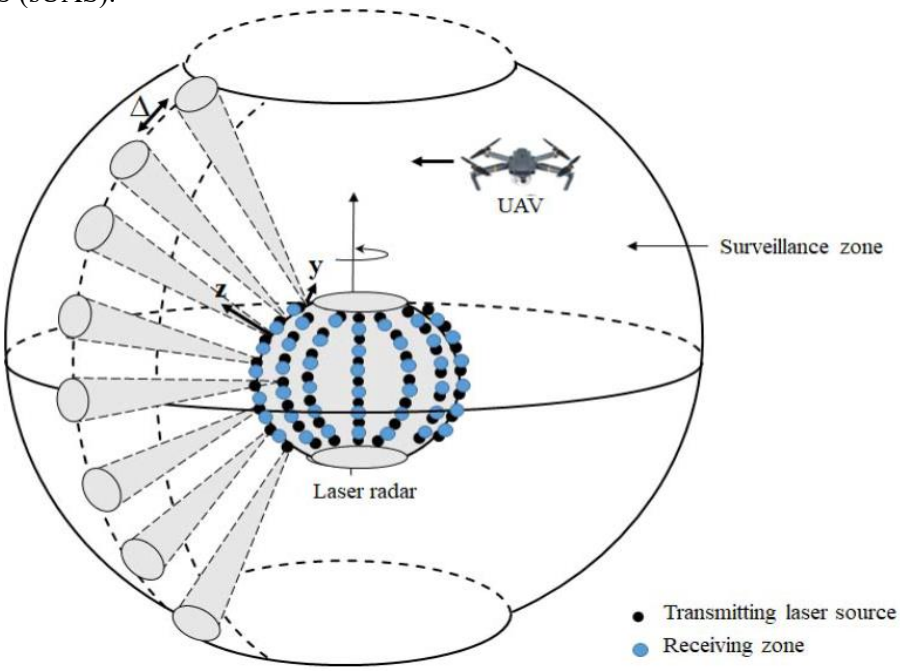

Figure 10: Utilizing a 360 ^{0} 3D LiDAR technology for sUAS detection.

- The key elements of the developed LiDAR data processing algorithm included
  - Reading data from the *.pcap* files to point cloud objects
  - 3D Segmentation
  - Creation of an enriched list of clusters
  - Comparison of clusters using Principal Components Analysis
  - Excluding stationary objects (ground, big objects, nonflying objects) by applying a variety of masks
  - Identifying and tracking multiple confirmed sUASs

Figure 10 shows an example of the algorithm output where multiple UAS can be reliably detected despite of a cluttered environment (trees with moving leaves, walking people, grass, etc.)

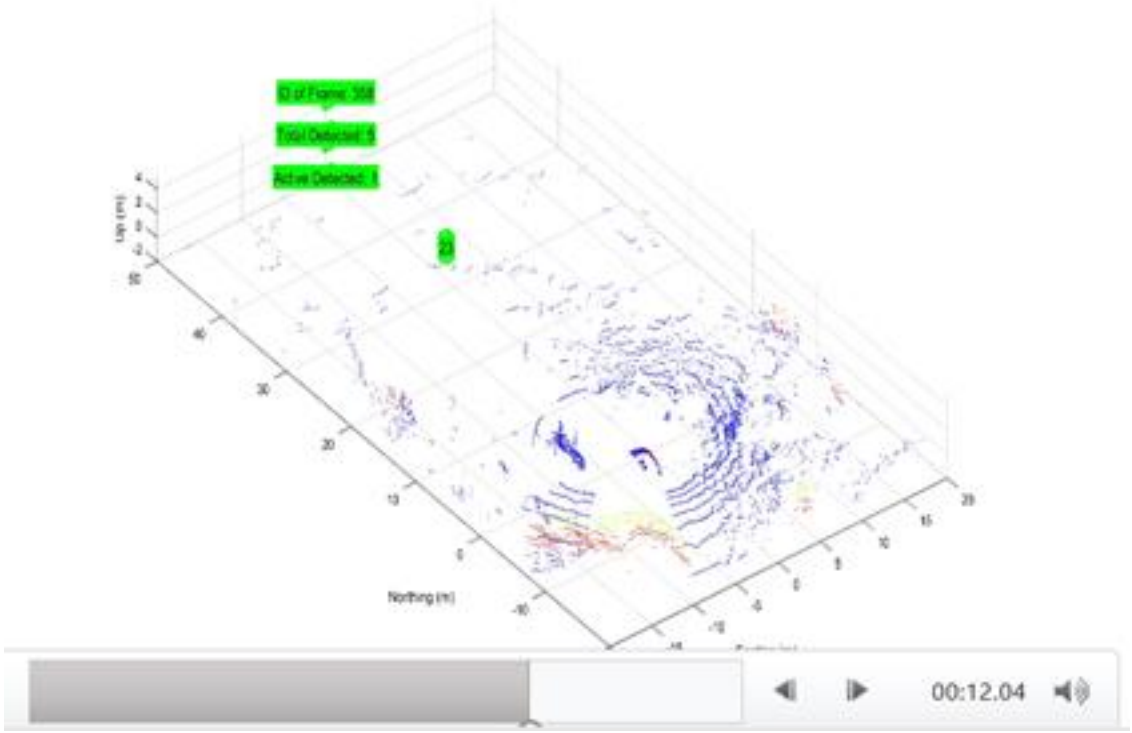

Figure 11: Screenshot of the playback when the fifth intruder sUAS is detected and tracked despite the very cluttered (from the LiDAR's standpoint) operating environment

- The detection range was found to be a major limitation (Fig. 4). On the other hand, this type of sensor is ideal for determining an accurate location of sUAVs, given that they are already detected (independent of their altitudes and speeds).

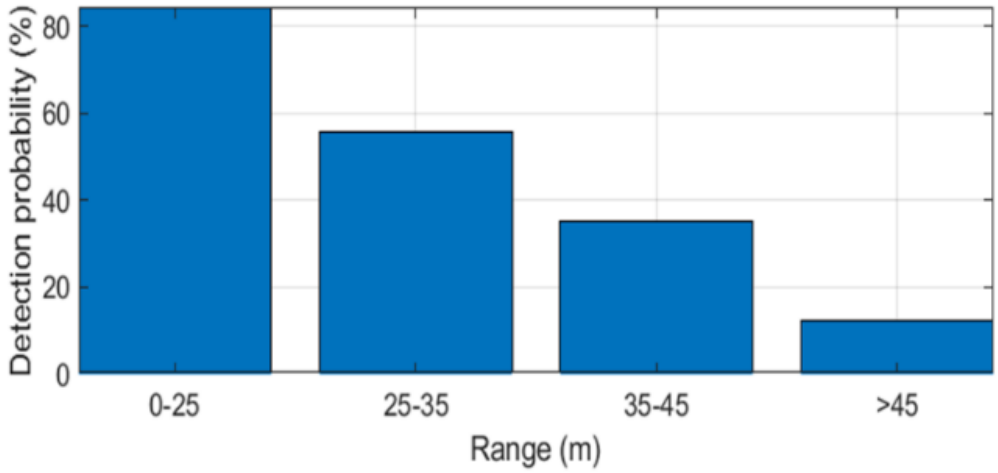

Figure 12: sUAS detection probability via range (specific to a relatively inexpensive Velodyne Puck LiDAR).

As a result, the detection system should probably use a variety of heterogeneous systems so that one sensor detects sUAS at a larger distance and another (LiDAR) uses a narrow band to allow more accurate detection/identification at farther distances.

- The CPU time required to process each frame of LiDAR data in the interpretive environment of MATLAB was about 0.1 seconds, meaning that the detection algorithm can run in real time, including onboard of a c-UAS (on a secondary single board computer).
- Further investigation may include coding the developed algorithm in Verilog and running it on a field-programmable gate array (FPGA). The parallelism algorithm execution that FPGA can provide could give the capability to add many more functionalities to the algorithm and result in in either increasing the effectiveness of detection or adding additional capabilities, while sustaining the real-time execution of the code.
- Further improvement of the algorithm could include incorporation of Artificial Intelligence-based techniques to assure proper object classification.
- Another extension could be prototyping a forward-deployed c-UAS system that would address the detection range issue. This involves miniaturization of the developed prototype and implementing it atop one of the larger drones available (e.g., Freefly Alta X).

Education:

Paschalidis, K., Detection of Small Unmanned Aerial Systems Using a 3d Lidar Sensor, MS Thesis, NPS, Monterey, CA, Sept. 2021.

Dissemination:

A paper is in the process of preparation for the conference on robotics.

Collaboration and Partnership:

None

Transition:

Potential follow-on funding through NRP, U.S. Army and U.S. Air Force. N9 - Warfare Systems has expressed an interest to support this research topic in FY22 already. There is an interest from COMSUBPAC too (the talks have started already). The U.S. Army TENCAP has installing a c-UAS CORIAN system in a close proximity of the McMillan airfield and is looking to collaborate on testing alternative technologies at Camp Roberts and Yuma Proving Ground.

III. COMMUNITY OF INTEREST

A. MEMBERSHIP

The CRUSER community of interest (COI) membership grew slightly to ~3200 members (Dec 2021). The membership breakdown is 55% general population, 24% education, 19% military, and 2% government.

B. MONTHLY MEETING PROGRAM

CRUSER holds a monthly community meeting generally on the first Monday or the month at the noon hour. In 2021, the meetings were held virtually using Zoom for Government. These monthly meetings are intended as information sharing forums for the entire CRUSER community of interest, and each month feature presentations from CRUSER funded researchers, CRUSER supported NPS thesis students, or any member of the non-resident CRUSER community that has a significant topic to share. In 2021, there were 11 monthly CRUSER meetings featuring 16 presentations.

Table 2: NPS CRUSER Monthly Meetings

Month	Presentation Title(s)	Presenter(s)
January	NPS - ONR Funding Opportunities for Student Theses	Quinn Kennedy, Operation Research Dept, NPS and Perry McDowell, MOVES Institute
February	Operationalizing Human-Machine Teams in Surface Warfare AUV Active Terrain Aided Navigation	Dr. Shelley Gallup, Information Sciences, NPS Doug Horner, Dept. of Mechanical & Aerospace Engineering, NPS
March	Legal Aspects of UxS SLAMR Update	Kristen Fletcher, Energy Academic Group, NPS Dr. Raymond Buettner, Director, Sea Land Air Military Research, NPS
April	Algorithms of Armageddon: What Happens When We Insert AI Into Our Military Weapons Systems?	George Galdorisi, Director, Strategic Assessments and Technical Futures, NIWC Pacific

May	Great Power Competition & Opportunities for UXV's in the Maritime "Gray Zone" DevOps to SpecOps: SOF Truths for AI Adoption	Dr. Corey Bergsrud, Engineer, Innovator, Leader, and Mentor, Naval Surface Warfare Center Crane Division Maj. Logan Marcucci, Defense Analysis Student, NPS
June	Accelerating Innovations for Robotics in Complex Real-World Environments	Dr. Timothy Chung, DARPA Program Manager
July	Developing Tactical Judgment in a Human-Robot Team	Dr. Donald Brutzman, Dept. of Information Sciences, NPS - Ethical Control of Unmanned Systems Dr. Robert Semmens, Dept. of Systems Engineering, NPS
August	How to Build Human-Autonomy Teams: Enabling Requirements, Adoption, and Verification	Dr. Douglas Van Bossuyt & Dr. Robert Semmens, Dept. of Systems Engineering, NPS with Bryan Mesmer, Dept. Industrial & Systems Engineering and Engineering Management & Kristin Weger: Dept of Psychology, Univ. Alabama, Huntsville
September	Modeling and Optimization of Adversarial Swarm Engagements Open System Modeling and Human Machine Teams	Dr. Abe Clark, Dept. of Physics, Dr. Isaac Kaminer, Dept. of Mechanical Engineering, and Maj. Wish, Combat Systems Program Office, NPS Dr. Mustafa Canan, Dept. of Information Sciences, NPS with Dr. Mustafa Demir, Ira A. Fulton Schools of Engineering, Global Security Initiative, ASU
October	Counter Aerial UxS Munition Delivery System: Overview and Status Update	Dr. Christopher Brophy and Dr. Joshua Codoni, Dept. of

		Mechanical and Aerospace Engineering, NPS
December	Predictive Failure Analysis for Autonomous Networked Ground Stations	Noah Weitz, Dr. James Newman, and Dr. Giovanni Minelli, Space Systems Academic Group, NPS
	Data Strategy for Unmanned Systems Field Experimentation (FX), Simulation and Analysis	Dr. Don Brutzman, Dept. of Information Sciences, NPS, Dr. Curt Blais, NPS MOVES Institute, and Kristen Fletcher, Energy Academic Group, NPS

IV. RESEARCH INFRASTRUCTURE

A. Joint Interagency Field Experimentation

Overview

The JIFX program exists to provide an opportunity for NPS faculty, students, private companies, and academia to demonstrate and evaluate new technologies related to the Department of the Navy and the Department of Defense research in an operational field environment. JIFX also serves to provide the operational community the opportunity to experiment with these technologies to better understand the capabilities that they may represent.

In 2021, JIFX hosted four quarterly events at both the NPS Field Laboratory at Camp Roberts Army National Guard Base and the Sea, Land, Air Military Research (SLAMR) Facility in Monterey, CA. In 2021, JIFX hosted 58 experiments and 792 participants.

JIFX 2021 Dates:

- JIFX 21-2 (1 – 5 March)
- JIFX 21-3 (24 – 28 May)
- JIFX 21-4 (23 – 27 August)
- JIFX 22-1 (1 – 5 November)

Primary Contacts

- Mike Richardson, JIFX Director, mrichard@nps.edu
- Ashley Hobson, JIFX Event Manager, ashobson@nps.edu
- Aurelio Monarrez, JIFX Flight Operations: amonarre@nps.edu
- Joseph Lukefahr, JIFX Network Operations: joseph.lukefahr.ctr@nps.edu
- Jonathan Coon, JIFX Data Management: Jonathan.coon@nps.edu
- Greg Arenas, Camp Roberts Facilities Manager: gaarenas@nps.edu

Accomplishments:

- In 2021, the JIFX program was able to maintain high-quality experimentation events despite the global changes due to the Pandemic. The program was adapted to host virtual events when in-person events were not practical and in the second half of 2021, the program returned to in-person events.
- In 2021, the JIFX program added the Sea, Land, and Air Military Research (SLAMR) facility as a secondary location for experiments during JIFX events. The unique SLAMR facility allows for experiments to utilize the aquatic tanks in extremely close proximity to the NPS campus. This also increased NPS student

participation during the event as they were able to easily travel to the SLAMR facility.

Education:

- In 2021, the JIFX program worked closely with students from several Naval Postgraduate School educational curriculums including 697 - Applied Design for Innovation; 595 - Information Warfare; and 474 - Doctor of Philosophy in Information Sciences.
- The team further supported research conducted by NPS' Center for Autonomous Vehicle Research (CAVR), California State University-Bakersfield Fabrication Lab as well as the University of Hawaii-Applied Research Laboratory (UH-ARL).
- Finally, JIFX team members hosted and supported to the 2021 Northern California-Monterey Regional Marine Advanced Technology Education Inspiration for Innovation (MATE II) Remotely Operated Vehicle (ROV) competition at the SLAMR Facility. MATE II is a National Science Foundation sponsored STEM Education and Workforce development program.

Dissemination:

- JIFX 21-2 Quicklook Report
- JIFX 21-3 Quicklook Report
- JIFX 21-4 Quicklook Report
- JIFX 22-1 Quicklook Report

Collaboration and Partnership:

The following companies and organizations participated in a JIFX event in 2021:

Table 1: JIFX Experiment Participants

- 3amInnovations
- Advanced Unmanned Aerospace
- Aerocine Ventures, Inc.
- AFRL/RW
- AFSOC A5RS
- Air Force Research Lab
- Ascent Solar Technologies
- AT&T Drone Operations
- AT&T Public Sector Solutions
- Aurora Flight Sciences
- Autonodyne, LLC
- Avalon Holographics
- AVX Aircraft Company
- Booz Allen Hamilton
- Nevada National Security Site - Special Technologies Lab
- Ocean Power Technologies
- Orb Aerospace
- Orgo
- Orion Labs
- Overwatch Imaging
- Persistent Systems, LLC
- Planck Aerosystems
- Point Source Audio
- Potter Technology
- Project OWL
- Promia Incorporated
- Rapid Imaging Technologies LLC

- BotFactory, Inc.
- Bounce Imaging
- BridgeComm, Inc.
- California State University, Bakersfield
- Caliola Engineering LLC
- Circle Optics
- CloudBees, Inc.
- Craitor, Inc.
- Crow Industries
- Department of the Navy Office of Small Business Programs (OSBP)
- DermaClip US, LLC
- DropDrone
- Edgybees Inc.
- Eikon Research
- Elbit Systems Ltd.
- Ex Scentia
- Exyn Technologies
- FNA, Inc
- Gantz-Mountain Intelligence Automation Systems
- Gates Defense Systems
- General Atomics Aeronautical Systems Inc.
- GLW Technologies LLC
- GreenSight
- HCI Energy
- Humaxa
- Innovative Algorithms
- Inpher, Inc.
- Insight Up Solutions
- Lumenier
- modelspace Incorporated
- Naval Warfare Studies Institute (NWSI)
- Rapid Reaction Technology Office
- Rhoman Aerospace
- Roving Blue, Inc.
- SeaSatellites
- SF Wireless Emergency Mesh
- Small Business Innovation Research (SBIR)
- Small Business Technology Transfer (STTR
- Sonardyne Inc.
- Southwest Synergistic Solutions, LLC
- Spectrabotics, LLC
- Splunk
- Spydar Sensors
- Star Solutions
- Strategic Mobility 21 Inc
- Target Arm Inc
- Tectus Corporation
- Telops USA
- TETAC, Inc.
- The Ulysses Group
- Thunderstorm
- TMGcore
- Torrey Pines Logic, Inc.
- U.S. Army CCDC Data & Analysis Center Abedeen Proving Ground, MD
- University of Nebraska - Lincoln
- Unmanned Vehicles and Autonomous Systems (UVAS) Working Group
- USASOC
- Valkyrie Systems Aerospace Inc
- Vidrovr
- Violet Defense, LLC
- Xona Space Systems
- Yotta Navigation

Transition/Future:

JIFX will continue into 2022 with the following events:

- JIFX 22-2: 14 – 18 February 2022
- JIFX 22-3: 16 – 20 May 2022
- JIFX 22-4: 15 – 19 August 2022
- JIFX 23-1: November 2022 (Dates TBD)

B. Sea, Land, Air, Military Research (SLAMR) Initiative

Overview

The Sea Land Air Military Research (SLAMR) initiative exists to build a culture of innovation for the Warfighter by rapidly extending the capabilities of the Naval Postgraduate School to provide a uniquely relevant graduate education, grounded in research, to current and future leaders of the Navy and Marine Corps.

SLAMR seeks to rapidly identify, explore, and evaluate new opportunities to innovate across the spectrum of Naval Postgraduate School research activities from facilities to business practices to evolving the digital enterprise. Using the Silicon Valley startup model, promising opportunities will be pursued aggressively and opportunities that do not pan out will be discarded rapidly.

Points of Contact

Primary Point of Contact: Dr. Raymond R. Buettner Jr., PhD.
(831) 656-3387
buettner@nps.edu

Additional Contacts: Mr David Mortimore
(360) 315-2213
E: dbmortim1@nps.edu
E: david.mortimore@navy.mil

Accomplishments:

- AT&T constructed a 5G tower on the NPS Beach Laboratory site to support the conduct of future information technology education and research projects.
- Sustained Aquatic Environment research environment under the facilities line of effort which expanded campus field experimentation capabilities to include maritime domain.
- Adams Communication & Engineering Technology (ACET) awarded a new $42.4M Task Order (TO) under the Defense Technical Information Center (DTIC) Information Analysis Center Multiple Award Contract (IAC MAC) by the Air Force Installation Contracting Agency to support the Naval Postgraduate School (NPS) for Unmanned and Robotic Systems Research. In addition to supporting JIFX and SLAMR experimentation the TO facilitated partner research including:
    - Mastodon Beast (Dismounted Multi-Channel TX with DF antennas)
    - Rogue AIS (Out of band AIS discovery, analysis and attribution)
    - Organic Precision Fires (Lethal drone support to dismounted Marines)
    - Spectrum Guard Elite (Evaluation of COTS RR/EMS support system)

Education:

- Hosted eighty students and faculty mentors from 2 middle and 6 high schools as competitors and a staff of twenty judges and officials for the NSF sponsored 2021 Northern California-Monterey Regional Marine Advanced Technology Education Inspiration for Innovation (MATE II) Remotely Operated Vehicle (ROV) competition at the SLAMR aquatic environment facility. Without NPS support the regional competition would have been cancelled.
- Supported the 2021 Department of Defense Artificial Intelligence Symposium and Tech Exchange which increased visibility for the NPS at the highest levels of DoD.
- Projects, Theses, & Dissertations
    - 5G Enabled Maritime Wi-Fi Buoy
    - Enhanced Corpsman to Hospital Optical System
- 5G integrated into courses
    - Information Warfare
    - Networks Operations & Technology
    - Computer Science
    - Electrical & Computer Engineering

Collaborations and Partnerships:

- The SLAMR aquatic facility served as a venue for four JIFX experimentation weeks hosting 12 experiments and 190 participants.

Future:

CRUSER and NPSF support launched SLAMR. Individual initiatives are likely to become self-sustaining but due to the nature of MILCON projects building out the facilities quickly to expand capacity and create a self-sustaining business model will remain a challenge. The following initiatives have been proposed to further advance the SLAMR goals:

- JDDE Proposal for EDEN
- RRTO (EDEN)
- RRTO (Unmanned logistics - WOC)
- OSD R&E/JIFX Support to SLAMR
- ONR/CRUSER Support to SLAMR
- Industry Partner Contributions (AT&T 5G)

- Future Projects, Theses, & Dissertations
    - Detecting and Tracking Dark Targets*
    - 5G for Naval Objectives*
    - Persistent and Emergent Maritime Domain Awareness*

C. RoboDojo

Overview

The RoboDojo is a dynamic innovation space (located on NPS campus in Root Hall, Room 125) where students, staff, faculty, and friends can come to learn about robot components and systems. The RoboDojo is designed to promote informal hands-on learning with open hours and volunteer mentors to help the NPS community learn about:

- rapid prototyping (e.g., with 3D printers and laser cutters).
- embedded computing (e.g., with Arduino and Raspberry Pi).
- basic electronics (e.g., with various electronics and breadboard components).
- robotic software programming (e.g., for Robot Operating System in Python).
- and more!

The RoboDojo also hosts various community-led workshops, including recent gatherings on topics ranging from Basics of Solidworks, Intro to Printed Circuit Boards, Intro to Laser Cutting and Engraving, and a Raspberry Pi Workshop. The RoboDojo represents a grassroots initiative to promote collaborative and community learning.

Points of Contact

- Primary Point of Contact:
  Kristen Tsolis, RoboDojo Director
- Additional Contacts:
  PO2 Melvin Llevado, enlisted support staff

Accomplishments:

- Workshop offerings during COVID: Pivoted to teaching online via Zoom while campus was closed. Offered on average 15 workshops per quarter while people learned from home. New workshop topics included “Underwater Positioning Systems”, “Wireless Communications Options for Robotics”, and “AUV Prototyping.” Each workshop is typically 1-2 hours long depending on instructor availability and student interest.
- RoboDojo lab personnel adapted to the remote learning environment by creating 12 new videos covering LiPo battery safety, Raspberry Pi, Arduino, and electronics.
- Currently utilizing some of these videos as pre-learning opportunities. Thus, limited workshop time provides a richer learning experience.
- Successfully launched first iteration of DA3304, Rapid Prototyping for the Warfighter course. Co-taught by DA and ME faculty. Students rapidly prototyped

unique quadcopters over the course of the class and tested them at our Marina test site.

- Developed small woodshop to support further prototyping efforts. Shop is expected to clear safety hurdles within the next month and should open on a limited basis in the new year.
- Supported two NPS "Human-Centered Design" workshops to discover opportunities available through emerging technologies. Concepts generated by these workshops can be used as thesis topics for students or may be adopted by the Navy to address complex fleet issues.
- Helped to host the NPS Makers Club and the Cyber Club with the goal of fostering innovative, fresh thinking on problems of interest to the Navy.
- Offered library of gear/parts that students can test/borrow without having to purchase gear. One example of this was a computer science student who wanted to test the security of communications protocols to sUAS, and this student borrowed both sUAS and our packet sniffing gear. Other students are utilizing our software defined radios, remote control gear, sUAS training equipment, land-based robots, etc.

Education:

- DA3304: Rapid Prototyping for the Warfighter (as mentioned above)
- Directly supported more than 50 thesis projects in the Mechanical Engineering, Systems Engineering, Computer Science, Physics, Defense Analysis, Space Systems, and other departments.
- Thesis Co-Advisor: "COTS DRONE DESIGN: A RAPID EQUIPAGE ALTERNATIVE FOR FORCE RECON COMPANIES"

Collaborations and Partnerships:

- CRUSER: RoboDojo's major sponsor
- ONR: Reservists sometimes help teach small workshops and offer technical expertise on student theses.
- Marine Corps Advanced Manufacturing Operations Cell: A former student and heavy user of the RoboDojo lab moved on to become head of this unit.

Future:

- Further develop of DA3304, Rapid Prototyping for the Warfighter (course)
- Generate additional videos explaining how to use rapid prototyping tools

- AIAA: possible collaboration to develop additional learning resources for students and possibly the larger community beyond NPS.
- Further develop woodshop to support student rapid prototyping needs.
- Continue to support outreach for local robotics teams and other STEM efforts. This is a mostly volunteer, student-run effort, and the lab provides gear, activity ideas, and technical expertise in support of this effort.

Figure 13: RoboDojo 2021

V. EDUCATION

A. Student Travel

Overview

As an incentive for NPS active-duty students to engage broadly with academic, defense and industry communities during their studies, CRUSER continues to support student travel when related to robotics and autonomous systems. Students often take advantage of this opportunity to participate in field experimentation, make site visits to sponsors, interview stakeholders or present their work at conferences and workshops.

Due to the COVID-19 pandemic, less student travel was executed in 2021.

Points of Contact

- Primary Point of Contact: Jean Ferreria, Operations Manager

Accomplishments:

During 2021, student members executed 30 travel events, with a total cost of $29k, related to CRUSER research projects. Destinations included, but were not limited to the following:

- Experimental rocket launches; April, July and October; Tehachapi, CA.
- JIFX participation and UAV swam flight testing; February, May, August,and November; Camp Roberts, CA.
- Collaboration meeting with US Army; West Point, NY.
- UUV experimentation; NUWC-Keyport.
- UAV experimentation; Fort Bragg, NC.

B. Robotics Engineering Graduate Certificate

Overview

In July 2020 the Robotics Engineering Certificate commenced its inaugural cohort. The demand was high enough to start another cohort in January 2021. For the first cohort 21 students were the first to graduate from certificate in June 2021. The second cohort just finished in December 2021. Interest still warrants another cohort in January 2022. Due to COVID, in-person labs have been converted into online assignments.

Points of Contact

- Primary Point of Contact:
  Dr. Brian Bingham, Professor
- Additional Contacts:
  Ms. Marianna Jones, Faculty Associate Research

Accomplishments:

In June 2021, the Robotics certificate graduated 21 students from the following commands, which emphasizes collaboration between Naval Research and Development Establishment (NR&DE) workforce:

- NIWC-Pacific
- NSWC-Dahlgren
- NAWS-China Lake
- NSWC-Carderock
- NUWC-Newport
- NUWC-Keyport
- NSWC-Port Hueneme
- ONR
- NRL

In December 2021, the Robotics certificate graduated 7 students, mostly from NSWC-Carderock, and one from NIWC PAC and NAVSEA.

Education:

The robotics engineering graduate certificate consists of the following sequence of foundational and applications-oriented distance-learning courses:

- ME3420 Computation Foundations for Robotics
- EC4310 Fundamentals of Robotics
- ME4822 Guidance, Navigation, and Control of Marine Systems or ME4828 4 Fundamental GNC Algorithms of Autonomous Robotics
- ME4800 Machine Learning for Autonomous Operations

Future:

In January 2022, we will start a new cohort of 21 students from the following commands:

- NAVSEA
- NSWC-Carderock
- NSWC-Dahlgren
- NSWC-Port Hueneme
- NSWC-Corona
- NAVAIR NAWC-WD China Lake
- Army Combat Capabilities Development Command Soldier Center
- NAVAIRSYSCOM
- Naval Air Warfare Center Aircraft Division (NAWCAD)
- Naval Facilities Engineering Services Center
- Submarine Force Pacific UUVRON-1

VI. CONCEPT GENERATION

A. Warfare Innovation Continuum

Overview

NPS Warfare Innovation Continuum (WIC) leverages classroom projects, theses, and research in advancing naval concepts, assessing new technologies, and developing tactics while enhancing our students' educational experience and sharpening their combat skills.

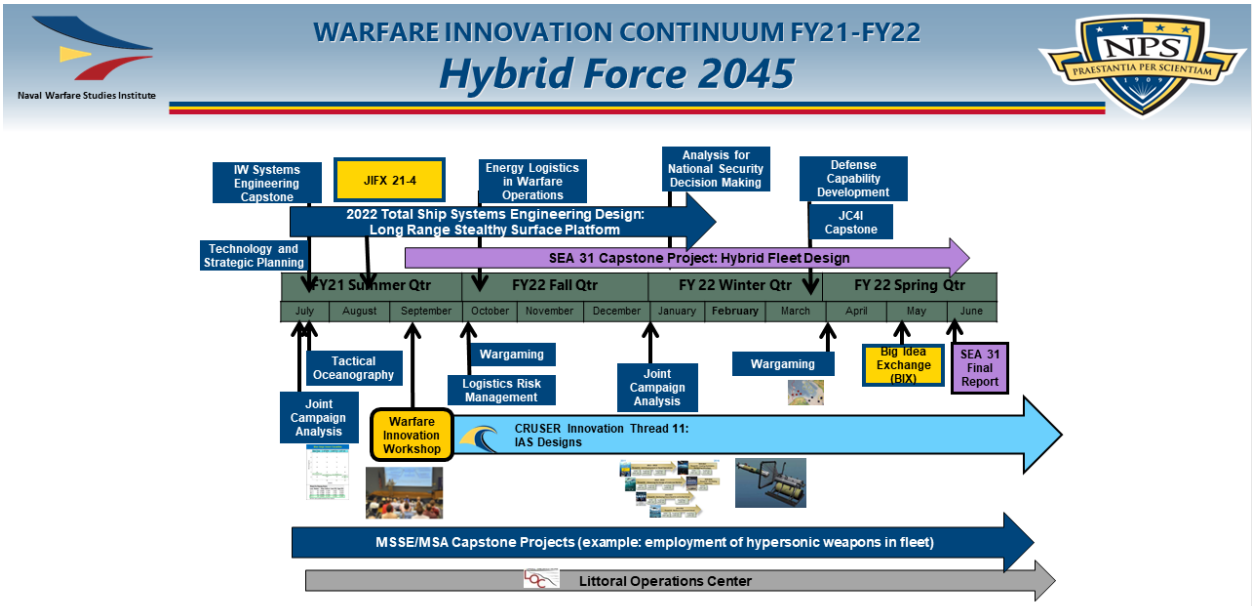

Figure 14: Warfare Innovation Continuum FY21-FY22: Hybrid Force 2045

The FY21-22 WIC "Hybrid Force 2045" is exploring future fleet design through a variety of perspectives and lenses. The envisioned future force will likely rely heavily on human-machine teaming and will require agility in response and reconfigurable assets driven by mission needs.

Cross-Campus, Cross-Curriculum Effort: The NPS Warfare Innovation Continuum provides a naval warfighting theme of interest to naval leadership for NPS capstone classes, student, and faculty research projects, CRUSER research threads, wargaming events, and workshops to rally behind. Traditionally involving over 400 sponsors, faculty and students, past themes include distributed maritime forces, warfare in contested littorals, undersea warfare, and the integration of unmanned systems in naval operations.

From Quantitative Assessments to Design: By synchronizing class and research efforts, a concept or technology's benefits and risks are better explored. For example, while the

Joint Campaign Analysis course quantifies the value of distributed operations, the wargaming class will develop red's response, the JC4I class will develop a distributed command and control system, and WIC Workshop propose new technologies to employ.

Leveraging an Academic Year: The Naval Postgraduate School's academic disciplines and research range from sound waves to strategy, from fluid dynamics to data analytics, and from robotics to acquisition. Leveraging this talent and our operationally experienced students to provide a broad look at employing new warfighting concepts or emerging technologies provides a robust assessment for Navy sponsors. The Warfare Innovation Continuum topics are introduced in July of each year which begins research threads lasting up to two years. The WIC's products are an executive summary of each classroom and research product.

Annual WIC Workshop: The Warfare Innovation Continuum (WIC) Workshop each September explores a problem space of particular interest to the Fleet and Force. Small teams of junior officers and early career engineers are facilitated through a rapid design process using tools of user-centered design to address a design challenge posed through a near peer near future conflict scenario to create concepts of operations and employment around emerging technologies. Each team presents their best three or four concepts on the final day of the three-and-a-half-day workshop, and these ideas are then developed by NPS researchers, students, warfare centers, and industry, academic, and allied partners.

In 2021, the Warfare Innovation Continuum Workshop titled "**Hybrid Force 2045**" took place 20-23 September 2021 both in-person on the NPS campus and remotely on Microsoft Teams. The design challenge for the September 2021 workshop was: How might emerging technologies, new operational concepts, and alternative fleet designs contribute to a more effective naval force across the spectrum from competition to conflict? How do the alternative fleet designs enhance the effectiveness and resilience of joint, combined and coalition forces across all domains?

The Warfare Innovation Continuum has served as a useful framework to look at a complex military problem space since 2014, and the WIC Workshop has been incorporated within the full WIC structure since the start. With the launch of the Wayne P. Hughes Naval Warfare Studies Institute (NWSI) the annual WIC Workshop will be replaced by several rapid concept generation workshops throughout FY22 to support individual NWSI Research Task Forces such as Task Force Overmatch and Task Force Gray Zone culminating with a larger Warfare Innovation Workshop in September 2022.

Points of Contact

- Primary Points of Contact: Jeff Kline, Professor of the Practice – NPS Operations Research Department (jekline@nps.edu) and Ms. Lyla Englehorn, Concepts Branch Lead – NPS Naval Warfare Studies Institute (NWSI) (laengleh@nps.edu)

Accomplishments:

- "Hybrid Force 2045" Warfare Innovation Continuum (WIC) Workshop, 20-23 September 2021: over 130 participants split evenly between the NPS campus in Monterey and the "Virtual Campus" via MS Teams addressed a design challenge. Final report is posted on the NWSI website (https://nps.edu/web/nwsi).
- Full WIC FY21-22 will be complete in June 2022 and a WIC "Hybrid Force 2045" Executive Summary report of activities will be available in July 2022 to inspire research on technologies which could be quickly integrated into the Fleet and Force.

Education:

- NPS Courses:
    - Technology and Strategic Planning Course
    - Energy Logistics in Warfare Operations Course
    - Analysis for National Security Decision Making Course
    - Defense Capability Development Course
    - Joint Campaign Analysis Course (x2)
    - Tactical Oceanography course
    - Wargaming Course (x2)
    - Logistics Risk Management Course
- NPS Capstones & Projects:
    - IW Systems Engineering Capstone
    - 2022 Total Ship Systems Engineering Design: *Long Range Stealthy Surface Platform*
    - JC4I Capstone
    - MSSE/MSA Capstone Projects (several)
    - SEA Cohort 31 Capstone Project: *Hybrid Fleet Design*
- Other NPS Education Alignments:
    - NPS Field Experimentation – Joint Interagency Field Experimentation (JIFX) (x4)
    - NPS Big Ideas Exchange (BIX)
    - NPS Littoral Operations Center research work (various)

Collaborations and Partnerships

- U.S. Navy Unmanned Task Force
- OPNAV N9I
- OPNAV N2/6

Future

The FY21-22 WIC “Hybrid Force 2045” will continue into FY22 courses and capstone projects as well as NPS research projects, and a final “Hybrid Force 2045” WIC Executive Summary will be available in September 2022.

VII. STEM Activities

With support from the ONR Naval STEM Coordination Office (NSCO, POC Kathleen Miranda), CRUSER championed several "Design Challenges" geared at high school students and through the online platform, Scoutlier. These specific challenges focused on Autonomous Systems, Cybersecurity, Climate Change, and Additive Manufacturing, with the focus of how autonomous systems integrate into these areas. These challenges provide STEM high school teachers with a hands-on curriculum around each central topic ending in a group design challenge where teams of students find solutions to a specific problem presented to them. Using the online platform, these challenges can scale across the country with ease. The four challenges for 2021 will be included in the upcoming "Discovery Day" at NPS in Spring 2022 to include a special session with Monterey County schools. These challenges can be found here: https://scoutlier.com/rapid-innovation-challenges/.