NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

CONSORTIUM FOR ROBOTICS AND UNMANNED SYSTEMS

EDUCATION AND RESEARCH (CRUSER)

2023 ANNUAL REPORT

by

Ashley Book

January 2024

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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 2023 annual report summarizes CRUSER activities in its tenth year of operations and highlights future plans.

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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 was founded in 2011 as a Secretary of the Navy (SECNAV) initiative to build an inclusive community of interest focused on the application of unmanned systems in military and naval operations. Funding for seed research activities is provided by the Office of Naval Research. 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 and 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 through opportunities at JIFX, UAS flights at the Monterey Bay Academy, and support for at-sea experimentation.
- 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 existing academic departments, groups, 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, consisting of the CRUSER directors, Vice Provost for Research & Innovation, 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.

D. FINANCIAL

The 2023 CRUSER Program received $3,800,000 from ONR (N0001423WX01071) in mid-January, with a period of performance end date of 31 Dec 2023. As of the date of 8 December 2023, the funding is 70% expended, 27% obligated/encumbered, with an unspent balance of 3%, which is planned to cover December labor.

II. SEED RESEARCH PROJECTS

CRUSER seeks to shape generations of naval officers through education, research, concept generation, and experimentation in maritime applications of robotics and autonomous systems. 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 Department of the Navy (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 projects. CRUSER seed 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 for national security reasons.

Table 1 summarizes the 16 CRUSER seed research projects for 2023 and the following subsections are detailed summaries of each project.

Table 1: 2023 CRUSER Seed Research Projects

	Principal Investigator(s)	**Project Title**
1	Prof. Don Brutzman Dr. Curtis Blais	Data Strategy for Unmanned Systems Field Experimentation (FX), Simulation and Analysis

2	Dr. Duane Davis Prof. Kevin Jones CDR Katy Giles	Tightly Coupled Formation Flight of Swarms to Support Extended Range and Deception
3	Kristen Fletcher Marina Lesse	The Role of Unmanned Systems in Meeting Climate Challenges
4	Dr. Britta Hale Aurelio Monarrez Joseph Lukefahr	UxS Manned/Unmanned Secure Teaming Platform Evaluation in Contested Littoral Environments
5	Prof. Douglas Horner Prof. Geoffrey Xie Prof. Ruriko Yoshida	Multirobot Temporal Logic Optimal Control
6	Prof. John Joseph	Persistent Smart Acoustic Profiler (PSAP)
7	Prof. Isaac Kaminer Aurelio Monarrez Joseph Lukefahr	Collaborative Hyper-Enabled Operations in Contested Environments (CHOICE)
8	Prof. Mark Karpenko	MAD-CAT: Modular Autonomous Drone-Configurable Aero Target
9	Prof. Emil Kartalov	Mechanical Design and COMSOL Analysis of Archimedes-Force Quiescent UUVs for Large-Scale Distributed Offensive Mine Operations
10	Prof. Sean Kragelund Prof. Violet Mwaffo (USNA)	Hybrid Swarm Attacks in Contested Environments
11	Prof. Violet Mwaffo (USNA)	Deep Neural Network State Estimation and Control in GPS and Radio Denied Environments

12	Prof. Mollie McGuire Aurelio Monarrez	Human-Autonomy Teaming: Control of Multi-Domain UxV's
13	Prof. David Ortiz-Suslow	sUAS-based Remote Sensing of Surface Waves and Breaking using an EO/IR Camera System
14	Prof. James Scrofani Prof. Ed Waltz Dr. Jihane Mimih	Orchestrated Autonomous Maritime Collection
15	Prof. Preetha Thulasiraman	Traffic Anomaly Detection and Analysis for 5G Enabled Autonomous Vehicle Systems
16	Prof. Joseph Klamo Prof. Alexander Laun (USNA) Prof. Justin Brown	Manipulating Control Surface Roughness on Uncrewed Underwater Vehicles to Achieve Scale-Independent Performance

A. DATA STRATEGY FOR UNMANNED SYSTEMS FIELD EXPERIMENTATION (FX), SIMULATION AND ANALYSIS

Participants

Principal Investigator (PI):

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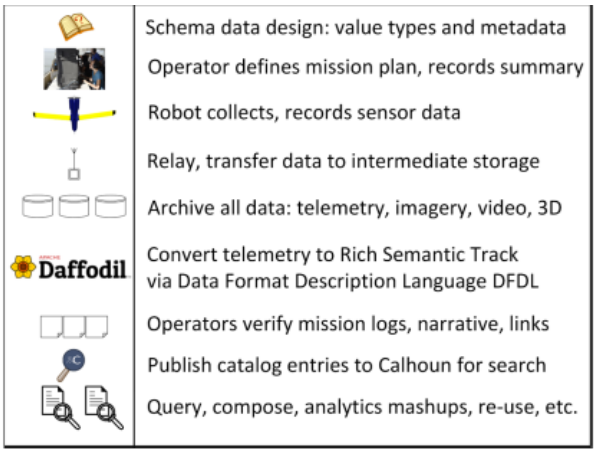

Figure 1: Robodata workflow for individual robot data collection that support experimental design. Data collection and storage enables recording, replay, smoothing, and visualization of robot track

Major Goals:

Data collection and analysis techniques for robot experiments are haphazard and incomplete. 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. Reusable end-to-end data workflows are needed. Building on multiple open standards, open-source tools, and authoritative data formats, ongoing NPS CRUSER work is focused on applying Data Format Description Language (DFDL) techniques to archival recording/playback of mission orders, recorded telemetry and sensor streams. This necessary capability may enable an even-larger context, namely a Data Strategy for Unmanned Systems field experimentation (FX), modeling and simulation (M&S) supporting Live-Virtual-Constructive (LVC) synthesis,

data repositories, and repeatable analysis. A full end-to-end toolchain built using open capabilities has the potential to address these important needs. This work is assembling the component technologies that together might establish such an information infrastructure. Failure to implement a shared data strategy blocks necessary interoperability of human-machine teams.

Accomplishments:

The scope of this work is very broad. Our approach encourages adoption of open standards and open source. We have shared assets or influenced outcomes in multiple project accomplishments. Our long-term objective is to establish best practices for robot data and metadata, serving NPS Navy and USMC across the full range of needs for research, development, test and evaluation, analytics and operations.

These broad goals have been supported by a broad range of activity during the past year.

- Attendance at most JIFX events, carefully reviewing data-collection practices and paths forward. Strengths and weaknesses with the legacy COPERS system have been carefully noted, as have the needs of NPS field experimentation participants. Integration of these activities into course efforts has shown a clear path forward enabling broader activities by NPS faculty and students.
- Multiple published references describe how a *bottom-up* **Data Strategy for Autonomous Systems** and a *top-down* **Ethical Control of Autonomous Systems** together provide an actionable and comprehensive strategy for testing AI-based robots. Together these approaches can evolve NPS FX towards capabilities towards becoming a Live/Virtual Test Range for development of autonomous systems by NPS faculty, students, and partners.
    - Deliberate ethical control of autonomous systems by humans is achievable and necessary, consistent with moral leadership and established policy.
    - Necessary robot reliability cannot be a side effect of untrustworthy probabilistic AI/ML black boxes - the human role in warfighting is essential.
    - Test and evaluation must be accomplished both virtually and physically. Coherent measurement and repeatability are essential for meaningful progress.

    - Pursuit of this approach can be scalable across all DoD programs and industry players whose system products hold potential for lethal/lifesaving force.
- 3D visualization is often thought of as requiring specialized platform-specific game software. This is not the case. Extensible 3D (X3D) is a declarative file format, royalty free with multiple implementations, that is patterned after HTML for broad scalability. Years of effort by NPS as part of the nonprofit Web3D Consortium has led to advancement of X3D Graphics Architecture version 4.0, with ISO publication pending as International Standard, culminating a 7-year-round of improvement over multiple prior versions, maintaining backwards/forwards capability and retaining X3D model re-use over the past quarter century. I remain chair of the X3D Working Group and was recently elected by ISO member nations participating in ISO Standards Committee SC24 to a 3-year term as Convener for Working Group 6, Computer Graphics.
- Improvement of multiple open-source codebases including
    - X3D-Edit Authoring Tool for 3D visualization models as an plugin for Apache Netbeans, the world's most popular Integrated Development Environment (IDE) for Java and other programming languages (over 10,000 installations since Spring 2023).
    - Major progress in opendis7-java open-source library for IEEE Distributed Interactive Simulation (DIS) protocol for shared communications within virtual environments, provide the common-denominator "glue" protocol for potentially connecting all manner of robot telemetry in Live Virtual Constructive (LVC) model visualization and mashups. Source-code version control on github gaining international contributions. Infrastructure improvements now include source-code autogeneration, threading protection, unit tests, and ongoing examples/assignments in version control.
    - The robodata project established initial NPS data-collection capabilities for a wide variety of unmanned system experiments, using Data Format Description Language (DFDL) for parsing robot telemetry. This standard annotates an XML Schema to formally map one set of data structures to another, automatically enabling both parsing and unparsing of specialty formats to a common baseline. Working closely with partners at MITRE and elsewhere, recent work

has successfully overcome several long-running challenges. We now map diverse robot telemetry formats via DFDL into savable DIS steam files in order to best support long-term archivability and LVE reuse of robot data.

Primary conclusion: the Data Strategy for Autonomous Systems is achievable for NPS Joint Interagency Field Experimentation (JIFX).

Primary recommendation: continue technology and deployment work proceeding in that direction, as outlined in proposed CRUSER work to establish such JIFX capabilities in CY2024.

Education:

- *C4913 Command and Control (C2) Capstone:* advanced-level students spend day at JIFX and report on it, also report on concepts/capabilities learned (and gaps observed) as part of final team project.
- *IS3460, Networked Autonomous Systems*: introductory-level students spend day at JIFX and report on it, also report on concepts/capabilities learned (and gaps observed) in final project.
- *MV3500, Networked Simulation*: course assignment with DIS protocol similar to data collection/conversion, continuing improvement each year.
- Proposed 4-course LVC sequence expanding on each of these capabilities
- Socialization with Information Sciences Ph.D. program, most of whom are distance scholars: they are now planning to hold their quarterly on-campus resident week 5-9 FEB to match JIFX 24-2. One student is considering X3D visualization of model-generated radar beam data, one is considering a comparative study of flatscreen and immersive headsets using X3D, and one is considering X3D modeling of NIWC Antenna Test Range.
- The current level of software programming activity is complex and beyond the skill sets of most NPS students. Nevertheless our work is producing software libraries and tools that many students might subsequently use with greater ease. No other thesis students yet, but we will continue pursuing IS, MOVES, CS curricula.

Dissemination

All work is published openly, building upon decades of progress.

Two chapters in forthcoming book:

- *Trolley Crash: Approaching Key Metrics for Ethical AI Practitioners, Researchers, and Policy Makers*, Editors: Peggy Wu, Michael Salpukas, Hsin-Fu Wu, Shannon Ellsworth, Elsevier, February 1, 2024. https://shop.elsevier.com/books/trolley-crash/wu/978-0-443-15991-6
    - Chapter 7, *Autonomy compliance with doctrine and ethics by using ontological frameworks: Shared precision and understanding between humans and machines*, Don Brutzman, Curtis Blais, Hsin-Fu Wu, Carl Andersen, and Richard Markeloff.
    - Chapter 11, *Designing meaningful metrics to demonstrate ethical supervision of autonomous systems: How do you measure that?* Don Brutzman and Curtis Blais

Book chapter for forthcoming 2024 Wayne Hughes retrospective, edited by Sean Barrett and Mie Augier for U.S. Naval War College (USNWC) Press:

- "Network-Optional Warfare (NOW) for Fleet Tactics and Naval Operations," Don Brutzman

Book chapter under preparation for forthcoming 2024 compendium, slideset available:

- *Cyber Warfare for Navies*, edited by Chris Demchak and Sam Tangredi, "Data centric security (DCS) for Network Optional Warfare (NOW)," Don Brutzman and Jeff Kline, U.S. Naval Institute (USNI) Press, Annapolis MD 2024. Avoids a vast set of security vulnerabilities and limitations associated with network protocols, directly applies to Data Strategy for Autonomous Systems.

Additional intellectual products:

- Participation in quarterly Naval AI Summit meetings, offering contributions and exposure of both NPS FX opportunities and data-strategy imperatives with participants. Of particular interest is consideration of a Robotics Warfare Specialist

(RW) for Navy enlisted personnel, and potential inclusion of NPS activities in AI, Autonomy and Field Experimentation as part of that proposed personnel pipeline.

- Technical Report, Don Brutzman, Curt Blais and Terry Norbraten, Data Strategy for Autonomous Systems Field Experimentation (FX), Simulation, and Analysis, annual update in preparation for publication December 2023. This revision will provide a full review and updates for nearly all sections of this 29-page report, including all items reported in this annual summary. Access note: the NPS JIRA website is currently restricted to NPS intranet while ITACS fixes some software-related security issues, restoration of full access is anticipated sometime in early 2024.

Collaboration and Partnership:

We have worked with numerous partners as contributors to JIFX and multiple standardization groups. Most of our external work has been with X3D partners.

- Improvements to NAVFAC/EXWC SPIDERS3D Virtual Environment for shared X3D visualization across FLANKSPEED and public Web.
- Overview projects at https://gitlab.nps.edu/Savage/Spiders3dPublic
- U.S. Naval Academy (USNA) performed a major study using X3D models of the entire campus – buildings, grounds, offshore, and utility tunnels – performed by various robots and humans performing LIDAR scans for publication in a comprehensive X3D modeling suite. This work visualized 5-40 year climate-change impacts to Annapolis campus and decided to raise the entire seawall by 3 feet. USNA and Naval Support Activity Annapolis (NSAA) have released an Installation Resiliency Plan that includes multiple screenshots of the X3D visualization. I met with USNA/NSAA principals during summer 2023 to review physical-security concerns and plan archival publication in SPIDERS3D.
- This is an excellent exemplar that can inform improvement of NPS campus X3D models and justify planning of an X3D model for all Camp Roberts facilities. The long-term goal is to build virtual test range capabilities for both USNA midshipmen and NPS students.
- Navy Expeditionary Warfare Center (EXWC), SEABEE, and contractor teams currently deployed using scanning robots for X3D modeling of Apra Harbor Guam and Peleliu.

- Initial SPIDERS3D Virtual Sand Table (VST) restored in MOVES Savage Lab, Watkins 273, using 3D printed models and vertical projection for collaborative group visualization.
- Equipment purchased for second VST, with installation requested by NPS Public Works in Professor Didoszak's TSSE lab at the opposite end of Watkins Hall (50m away). These two rooms can serve as laboratory basis for remote 3D collaboration testing, with other Naval commands welcome to join.
- Recent addition of WebXR standard capabilities to the open-source X3DOM library for HTML allows any headset to view X3D models using Web technologies, within regular Web browsers, requiring no other software or license.

Transition:

Numerous parts of this work are transitionable by design. A selection of current discussions follow.

- Discussion co-founder of QuantumShield at last summer's JIFX have led to a long-running discussion about combining their quantum-resistant encryption technology together in proposal showing Data-Centric Security viability for robot-collected data, compatible with NIST Zero-Trust Architecture (ZTA). Proposal likely next quarter.
- Ongoing discussions with Mark Lucas, Technical Director, Operational Test and Evaluation Force (OPTEVFOR) regarding potential partnerships with NPS centered on field experimentation (FX), robot data collection, and applied student research.
- We are reaching out to multiple practitioners and principals in the Navy and DoD regarding Ethical Control, providing advanced courtesy chapters for their consideration. We expect steadily growing interest, and will maintain the stance that real-world robot testing is necessary for meaningful verifiable progress.
- Even though not currently supported by RTX IraD funding, we continue to communicate frequently and propose collaborative efforts. They are a most worthy partner whose greatest potential benefit might be to show that NPS innovations can be applied scalably by industry. It is noteworthy that all four editors of the *Trolley Crash* volume to be published by Elsevier are active RTX employees.

- The recent quarterly Naval AI Summit included a major briefing by is chief data scientist for TF59, testing a wide range of contractor owned contractor operated (COCO) robots with all collected data now owned by the Navy. Several exercises each quarter are uploading telemetry data, imagery, video, and mission metadata to the government cloud. We have performed a close examination of his robot data and metadata collection plans. We believe that the TF59 data strategy can benefit from our DFDL techniques to overcome "tower of Babel" pathologies associated with diverse commercial robot formats. We further see how we might evolve this data strategy, and NPS JIFX data-collection practices, to become compatible with TF59 cloud-centered approaches. Further investigation is warranted. Given multiple resonances with NPS mission of graduate education, research and innovation, a Memorandum of Understanding (MOU) between TF59 and NPS is likely warranted as well.
- Further transition discussions are expected and welcome. This project is not designed for year-to-year incremental funding and continuation survival, rather it is designed to connect practitioners, analysts, and leaders for Naval decision advantage. We look forward to further inquiry and collaboration in all directions.

B. TIGHTLY COUPLED FORMATION FLIGHT OF SWARMS TO SUPPORT EXTENDED RANGE AND DECEPTION

Participants

Principal Investigator (PI):

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Co-PIs:

Dr. Kevin Jones, Research Associate Prof., Mechanical & Aerospace Eng.

CDR Kathleen Giles, USN, PhD, Assistant Professor, Systems Eng.

Major Goals

The primary goal of this research was to investigate the reduction in average induced drag of the UAV flock by flying in close formation during transit. While previous ARSENL work focused primarily on large numbers of heterogeneous vehicles operating in multiple domains, this research utilized smaller numbers of homogenous aircraft to concentrate on more precise relative positioning of individual aircraft. Trailing aircraft in a tight formation benefit from the upwash created by wingtip-vortices shed by the aircraft ahead of them. The scale of the benefit varies depending on the aircraft used, the specific flight conditions and how precisely the relative positions are, but under the right circumstances, the theoretical benefit can be on the order of a 50 percent reduction in induced drag. A potential side benefit of transiting in a tight formation is one of tactical deception. Ground and air sensors may identify the flock of smaller vehicles as a single larger vehicle, or possibly as a flock of birds. Once the swarm is close enough to be detected as a swarm, the aircraft are more likely to be in a position to successfully carry out their mission even if opposed.

In order to realize the primary research goal of tight formation flight, a number of foundational capabilities need to be developed. This first iteration focused on these capabilities to include flight control tuning and software and hardware upgrades for the test platform and characterization of its wingtip vortices.

Accomplishments:

This research was conducted along three lines of effort: test platform upgrades, formation flight behavior development and evaluation, and wingtip vortex characterization. Research accomplishments will be discussed in the context of these efforts.

1. Test platform upgrades

The existing ARSENL Penguin UAV was selected as the test platform because its flight characteristics were deemed most appropriate for close formation flight. It did, however, require modifications before formation flight experiments could be conducted.

a. Autopilot firmware update and parameter tuning

ARSENL fixed-wing UAVs, including Penguin, utilize Pixhawk-family autopilots and open source ArduPilot firmware. The firmware in use upon commencement of this research was an ARSENL-specific version of ArduPlane version 3.8.5, several iterations behind the community version 4.4.0. In order to take advantage of its newer capabilities, the community version of ArduPlane V4.4.0 was modified to incorporate ARSENL-specific functions (e.g., failsafes). The first several flights focused on validating these firmware changes and conduct tuning to improve the precision and predictability of flying qualities to support formation flying.

Proportional-integral-derivative (PID) controllers are commonly used in UAS for flight stabilization and autonomous path-following. The first field experiment focused on tuning the gain of the flight parameters of the PixRacer R15 autopilot. Establishing an appropriate set of pitch and roll parameters was a prerequisite for the predictable and stable formation flying. Flight parameter tuning was accomplished with the default Ardupilot flight parameter settings as a pre-tuning baseline using the Ardupilot AUTOTUNE mode for both pitch and roll axes. While in AUTOTUNE mode, the Safety Pilot rapidly commanded full deflection of the elevator and ailerons multiple times to capture the respective tuned parameters for pitch and roll. Autopilot messages were monitored in Mission Planner (via a temporarily installed telemetry radio) to determine when each channel was complete. Mission Planner and MavProxy were used to monitor airspeed and altitude for consistency. The pitch and roll parameters were saved in log files for future use.

After completing autotune for the pitch and roll flight parameters, we used the Ardupilot Total Energy Control System (TECS) tuning guide to tune the TECS algorithm that manages the throttle and pitch angle inputs to control aircraft altitude and airspeed. Proper TECS configuration improves aircraft vertical flight path and airspeed control and aircraft endurance by

using a generalized multi-input/multi-output (MIMO) control strategy to ensure the aircraft maintains the desired energy state for the given flight conditions. Having an appropriately tuned TECS algorithm was considered a prerequisite for safely decreasing the spacing between aircraft in the formation. The following parameters were changed from the baseline settings:

- TECS_TIME_CONST was changed from 7 to 8 to reduce altitude oscillation.
- 1228: LIM_PITCH_MAX was changed from 20 deg to 22 deg
- 1232: TRIM_ARSPD_CM was reduced from 15 meters per second to 12 m/s and later adjusted to 14 m/s

The following additional TECS parameters were adjusted after observing several aircraft landings that appeared to be fast and with excessive pitch down:

- TECS_LAND_ARSPD
- TECS_LAND_SINK
- TECS_LAND_THR

These parameters were saved in log files for future use.

Following flight control parameter tuning, battery data was collected in support of post-flight current calibration to more accurately predict voltages during high current draw maneuvers. Results were used to update battery parameters in the autopilot to reduce false-positive battery failsafes brought on by power-transient maneuvers.

b. Camera installation and configuration

Formation and high-altitude communications-relay Penguins were equipped with the HD4K camera. Post-flight video review from initial flights with the camera indicated that vibrations from the camera mount reduced the video quality. The camera mount (which also holds the pitot tube) was redesigned (Figure 2) to reduce video jitter, and improved performance was noted on subsequent flights. Several flights were conducted with the camera configured with no filter and with ND8, ND16, and ND32 (darkest) filters. Upon post-flight review, the ND8 filter provided the best quality video for spotting the lead aircraft during the midday Camp Roberts sun.

Figure 2: Redesigned camera mount shown with filter installed.

c. Wingtip LED placement

Directional LEDs were added to the wingtips for eventual use by trail aircraft to fine tune their formation position. A number of configurations were tested progressing from a single LED on one wingtip to a final configuration consisting of a cluster of 3 green LEDs on the right and 3 red LEDs on left (Figure 3). The LEDs are lensed, concentrating light emissions in a 15-degree cone. The configuration with 3 LEDs on each wingtip provided a broader range of high intensity light.

Figure 3: Wingtip LED clusters with 3 red LEDs on the left wingtip and 3 green LEDs on the right wingtip.

2. Formation flight behavior development and evaluation

A formation flight behavior was implemented in the ARSENL swarm system in support of previous work; however, it did not control the formation aircraft's position accurately enough to

conduct safe close-formation flight. It was also noted that exploitation of the lead aircraft wingtip vortices would be most effective over long, straight flight paths. The ARSENL system, however, requires continuous air-to-ground communications making operation over extended distances difficult.

A new ARSENL behavior was developed to facilitate communications over longer flight paths: the Long Swarm Transit tactic. The Long Swarm Transit tactic was designed to control a swarm transit along a path as a group of individuals, as a formation, or as a flock (Boids). Regardless of the selected transit method, this behavior selects one aircraft to serve as a high-altitude communications relay for the group. The ARSENL application-layer communications protocol was simultaneously modified to allow certain messages to be relayed by an airborne asset to effectively double air-to-ground communications range.

Following development of the Long Swarm Transit tactic, the embedded Formation Transit play was upgraded to facilitate closer positioning. First, the proportional steering control was replaced by an L1 controller that steers towards predicted position 150 meters ahead of current "ideal" formation position. This resulted in qualitative performance improvement to the behavior in the form of smoother arrival at the formation position. No quantitative improvement to the final formation position accuracy was noted, however.

A PID speed controller was implemented to improve longitudinal formation positioning accuracy. The controller was implemented so that speed was only actively controlled when the UAV was aligned with both the lead UAV and the desired formation position, so the approach phase was unmodified. The controller was tested with good results in the ARSENL Software-in-the-Loop (SITL) simulation environment with the following controller constants (they were intentionally conservative in order to ensure safety of flight during initial field tests):

- $C_P = 0.04$
- $C_I = 0.00$
- $C_D = 0.015$

Of note, the integral term was set to 0.0 to prevent any "hunting" that might lead to a collision when tight positioning was ordered. Field experiments were safely conducted with ordered

formation spacing progressing from 25 meters down to as little as two meters (Figure 4). Post event analysis indicated that the trail aircraft reliably took position and stabilized approximately three meters behind the ordered position. Typical results are depicted in Figure 5 (positive longitudinal distance indicates that the ordered position was forward of the formation aircraft).

Following safe demonstration of the formation behavior, the SITL environment was utilized to experiment with more aggressive PID constants (including a non-0 integral constant). The following values were utilized to obtain the results depicted in Figure 6 for an ordered formation spacing of two meters:

- $C_P = 0.175$
- $C_I = 0.075$
- $C_D = 0.15$

Once the formation UAV fell into position, it reliably stayed longitudinally within 0.1 meters of the ordered formation position. These results were verified over multiple experiments in the SITL environment.

Figure 4: The view of 152 from 153 shown in step-down trail. LEDs on the wingtips are visible.

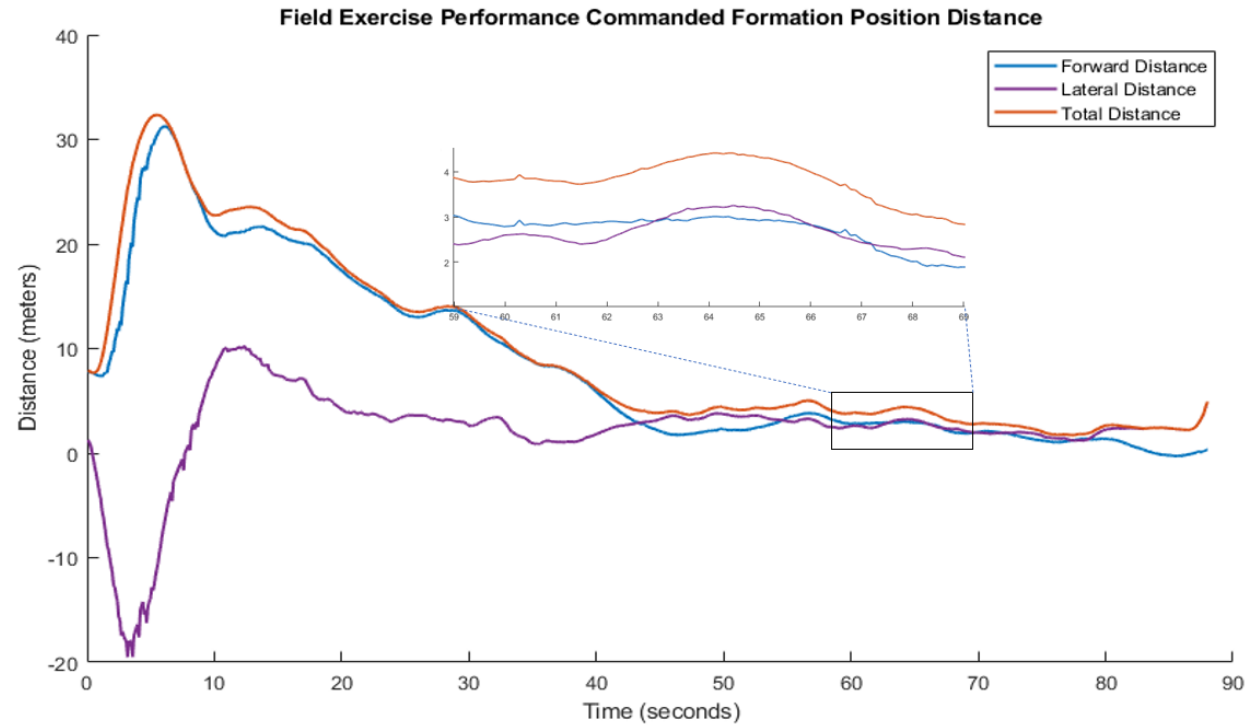

Figure 5: Initial field experiment deviation from desired formation position using initial PID coefficients with an ordered spacing of three meters. The formation UAV stabilized roughly three meters behind the ordered formation position.

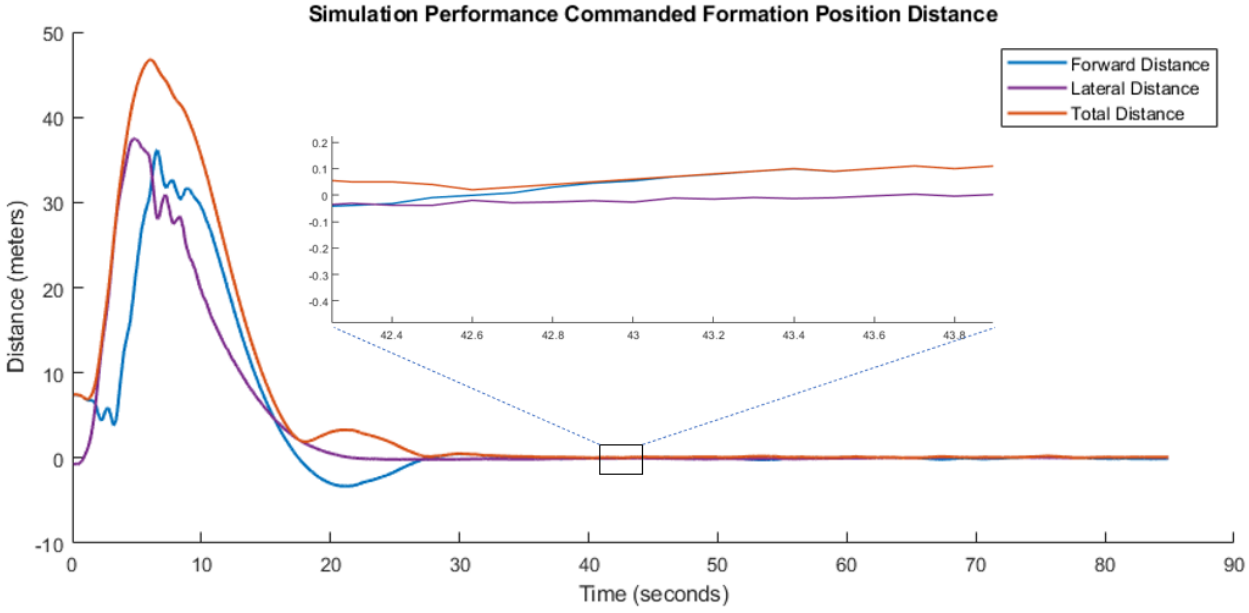

Figure 6: SITL simulation environment deviation from desired formation position with updated PID coefficients and an ordered spacing of three meters. The UAV reliably stabilizes within 0.1 meters of the ordered formation position.

Field experiments were conducted with the revised PID values on 8 December 2023. Unfortunately, the results were actually worse than those observed on previous exercises with the less aggressive coefficient values (Figure 7). This was attributed to differences in airspeed calibration between the lead and formation UAVs. Specifically, the baseline airspeed of the lead aircraft was observably faster than that of the formation aircraft despite both being set to the same value (14 meters per second). This made it difficult for the formation aircraft to obtain the ordered formation position even with the non-zero integral term. As the figure indicates, the formation aircraft continued to approach the ordered formation and achieved a final longitudinal distance of approximately six meters when the behavior was terminated. It is likely that the ordered formation position would have eventually been reached; however, safety of flight considerations prevented runs long enough to verify this.

A summary of the individual aircraft configurations and flight summaries for field experiments is provided in Table 2 and Table 3 respectively.

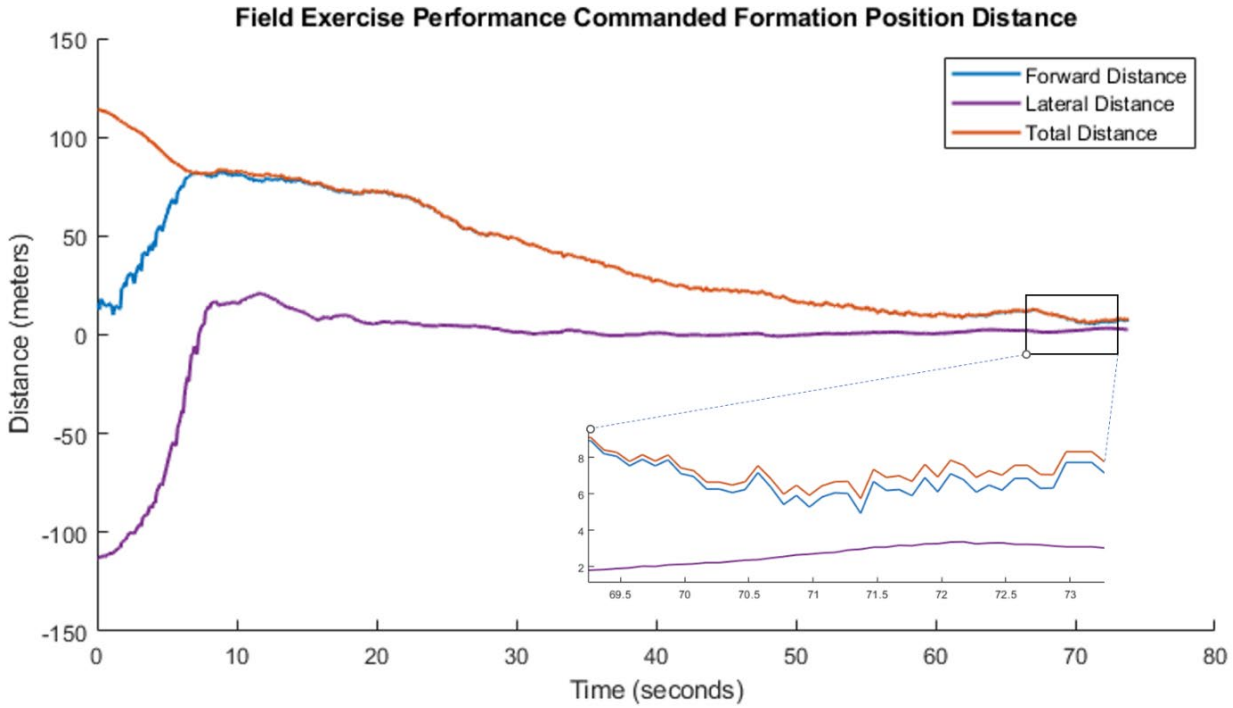

Figure 7: Final field experiment deviation from desired formation position with updated PID coefficients and an ordered spacing of three meters. The UAV approached to within approximately 6 meters of the ordered formation position.

Table 2: Aircraft Configuration

Aircraft	152	153	154	155
Autopilot computer	PixRacer 1.5	PixRacer 1.5	PixRacer 1.5	PixRacer 1.5
Payload Computer	Odroid C0	Odroid C4	Odroid C0	Odroid C0
Ardupilot software	ArduPlane 4.4.0 NPS dev	ArduPlane 4.4.0 NPS dev	ArduPlane 4.4.0 NPS dev	ArduPlane 4.4.0 NPS dev
Camera	N/A	4K	4K	4K
Camera filter	N/A	None, ND8 (primary), ND16, ND32	None	None
Wingtip lights (Sep-Dec events)	Left: red single, then tri-LED Right: green single, then tri-LED	None	None	None

Table 3: Summary of Sorties and Flight Hours

Field experiments	7
Sorties	19
Flight hours	7+13
Aircraft flown	152, 153, 154, 155

3. Characterization of trailing vortices

During this effort, a student, LCDR Ruben Jarillo Lopez, conducted related research on the aerodynamic performance of SUAS wings, and of interest here, on the characterization of the trailing vortices, using a several commercial Computation Fluid Dynamics (CFD) solvers. His work will help guide precision positioning of trailing aircraft for maximal gain from vortex lift.

Education:

Theses supported:

"Formal Proof and Performance Testing of the Unmanned Vehicle system Logging Protocol," Duvio, D., September 2023.

"Numerical Simulation of a UAV Wing and Several Modifications to Improve Range and Endurance," Jarillo Lopez, R., December, 2023.

Classes supported:

CS4313: Advanced Military Robotics

Dissemination:

Given its preliminary nature, no publications or presentations have been submitted for this work. Publications are anticipated once final results are collected and follow-on work is commenced.

Collaboration and Partnership:

Per the proposal, informal contact was maintained with Drs. Anthony Calise and Are Glezer from Georgia Tech over the course of this work, however a formal relationship was not established.

Transition:

Given the preliminary nature of this work (and the fact that it was only partially funded), the project is not ready for transition at this time. ARSENL will continue to pursue funding to further this work and will identify students to contribute through thesis and capstone projects in the meantime.

C. THE ROLE OF UNMANNED SYSTEMS IN MEETING CLIMATE CHALLENGES

Participants

Principal Investigator (PI):

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Students:

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Rebecca Grippo, Roger Williams University School of Law (3L)

Major Goals

The project objectives of the project were to (1) provide an analysis of the intersection of UxS and climate change to provide a foundation for the use of UxS in climate mitigation and adaptation moving forward; (2) analyze whether the proliferation of UxS reliant on fossil fuels reduces the ability to meet net zero goals and the impact of electrification of future UxS; and, (3) propose policy and guidance options to address the role of UxS in meeting U.S. and international climate challenges. Research also included an analysis of FVEY countries definitions of unmanned systems to advance legal clarity around whether they are vessels for purposes of international law.

The team conducted research on how UxS are used in the environment and the role they play in both adding to and reducing emissions and gathering data relevant to climate change. Research also focused on the status of electrification of UxS and advances in maritime recharging options for UxS. Finally, the team analyzed agreements that may apply to the environmental impacts of UxS (particularly abandoned systems) and what regions may have significant gaps in policy around UxS such as polar regions.

Accomplishments:

Role of UxS in Meeting Climate Challenges Report - The primary outcome is a report detailing how UxS contribute to climate change monitoring, mitigation and adaptation. The report

includes key examples of the use of UxS for these efforts, along with recommendations for policies that can solidify and strengthen the role of UxS in climate change actions. A briefing of the Role of UxS in Meeting Climate Challenges will be offered to a CRUSER meeting in spring of 2024. The full report will be submitted in December.

Key findings include:

- Climate mitigation requires identifying and quantifying sources and amounts of greenhouse gas emissions and UxS are already playing an important role in environmental monitoring and data collection, including being equipped with high-performance sensors to monitor and map the most climate-damaging emissions.
- UxS are usually smaller and lighter than their crewed counterparts and, even if they rely on fossil fuels, they generally emit fewer emissions. However, to truly play a role in reducing emissions, UxS must move toward designs that are, ideally, electrified or, at a minimum, fueled with sustainable fuels as opposed to traditional high-emission fuels.
- To enable these systems to best contribute to monitoring, mitigation and adaptation, gaps in governance structures must be addressed, particularly in the Arctic region where climate change is occurring faster than anywhere else on earth and countries are vying for valuable resources under melting sea ice.

An outcome includes findings related to the definition of UxS in FVEY countries' policies to determine whether there is enough uniformity to define UxS as vessels or ships for purposes of customary international law. The analysis revealed there is not such uniformity but provides insight into how such uniformity may be achieved in the future. This analysis is relevant for UxS used in climate change monitoring, mitigation, and adaptation and for other maritime uses.

Education:

Summer interns conducted research on the definition of UxS in FVEY countries' policies to determine whether there was enough uniformity to define UxS as vessels or ships for purposes of customary international law.

Dissemination:

Fletcher, Lesse, Presentation to NPS Meyer Scholars (January 2023).

Fletcher, Lesse, Podcast Interview, AI with AI (February 2023).

Fletcher, Lesse, Briefing, CRUSER Monthly Meeting (June 2023).
Lesse, Participant, Team Member, U.S. Coast Guard Evergreen Event on UxS (September 2023).
Milio, Theresa, Report, *Classification of Unmanned Maritime Systems by FVEY Countries* (October 2023).
Lesse, Workshop Lead, AI Law and Ethics, AI Strategic Challenge, The Technical Cooperation Program (October 2023).
Lesse, Planning Team Member, Moderator, AI and Climate Change (AAAI Symposium) (November 2023).

Collaboration and Partnership:
The Technical Cooperation Program (TTCP) – Through the Artificial Intelligence Strategic Challenge, PI Fletcher and Lesse have participated in the Law and Ethics Theme Team with colleagues from the UK, Canada, Australia and New Zealand. In 2023, Lesse took a lead role in several workshops related to UxS and AI.
U.S. Coast Guard – Lesse contributed information on law, policy and UxS to colleagues at the 2023 EVERGREEN event focused on UxS and participated as a team member (September 2023).

Transition:
NRP: Lesse is part of an NRP-funded project for FY24 that includes law and policy work related to the use of UxS in the Arctic region. Results of this work will be presented to ONR and relevant colleagues.

FERDP: Fletcher will incorporate findings related to UxS and climate change into FERDP-funded work on climate security and climate literacy.

The team hopes to continue the legal and policy research related to UxS but has so far been unsuccessful in finding funds dedicated for such work. Researchers will continue to socialize this work at NPS and throughout the Navy to identify funds to support further UxS law and policy research.

D. UXS MANNED/UNMANNED SECURE TEAMING PLATFORM EVALUATION IN CONTESTED LITTORAL ENVIRONMENTS

Participants:

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Major Goals:

Building on previous work, we sought to continue evaluating emerging network security architectures and protocols and their applicability in enabling secure yet disruption-tolerant data exchange among multi-domain teams of autonomous unmanned vehicles (UxV) operating in contested littoral environments. Our Intent was to ascertain which communications security

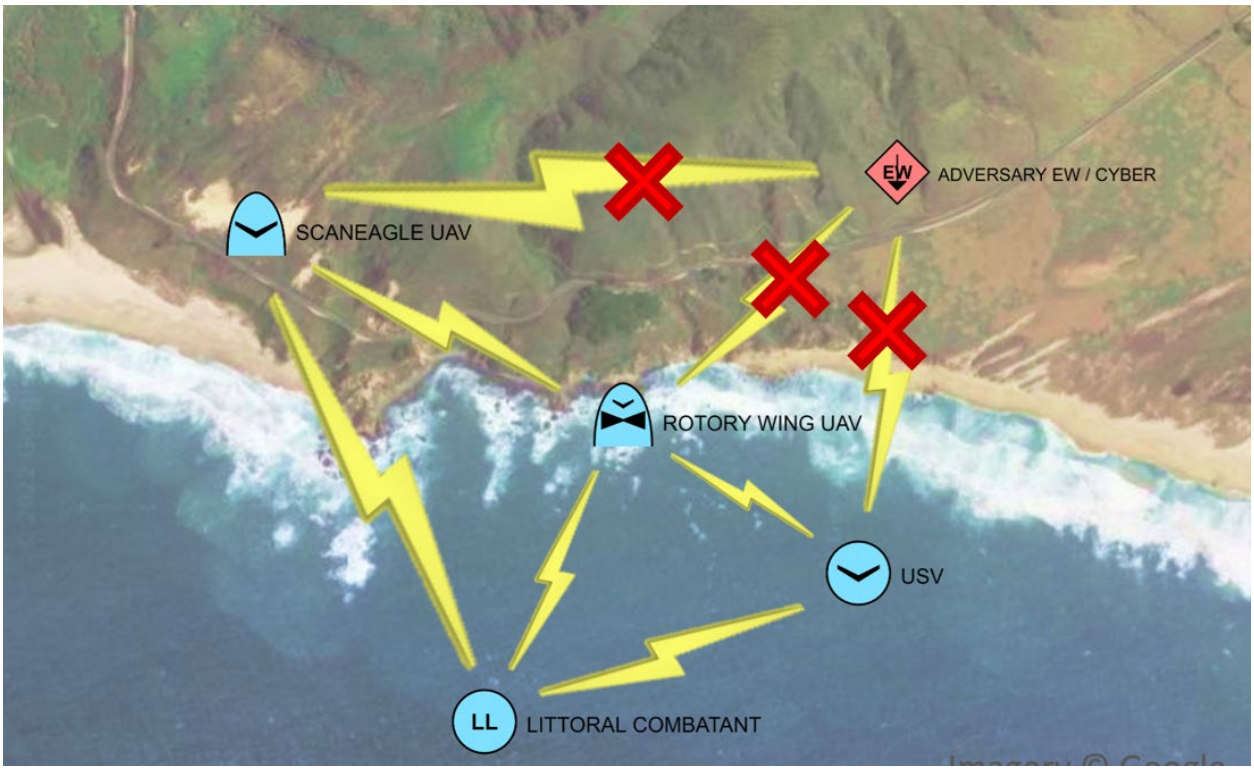

Figure 8: Notional concept of operations to be supported by MLS prototype software

protocols best address the Navy's needs in enabling development of this critical capability. Our major goal under in this project is to develop, test, and demonstrate a proof-of-concept implementation of Messaging Layer Security (MLS) in the context of securing group communications between computer systems with the intent towards usability on autonomous unmanned vehicles (UxV).

Figure 8 depicts a notional concept of operations (CONOPS) to be supported. Our original approach included field experimentation in support of this CONOPS. In support of our field experimentation plan, we successfully conducted preliminary flight testing with hardware that would run our prototype software system. However, administrative events outside our control rendered us unable to execute the culminating field event within the period of performance. Nonetheless, we adjusted and continued to follow the proposed approach, reiterated here. We revised and expanded a previously implemented prototype software system, and then we designed and conducted proof-of-concept demonstrations in a laboratory setting using variants of currently fielded US Navy UxV assets and tactical communications equipment.
Furthermore, we tested the power outputs and radio frequency (RF) footprint of MLS vs another standard protocol (TLS) for securing connections, with results pointing towards both the lower power output and less detectability of MLS. This supports insights in protocol selection for UxV use in contested zones.

In executing this project, we have gained a better understanding of the applicability of MLS as a protocol and architecture for securing communications within a manned/unmanned team during execution of this uniquely naval mission set.

Accomplishments:

- Developed prototype MLS secure publish/subscribe messaging relay software
    - Uses OpenMLS 0.5, an open-source reference implementation of the MLS protocol
    - Provides functions for encrypting messages, using OpenMLS, for messaging among groups of more than two members

    - Manages group state and key updates as group size increases, i.e. for new members
    - Options for underlying network transport architectures:
        - Local area network (LAN), using mobile ad-hoc network (MANET) radios to represent line-of-sight (LOS) communications architectures
        - Internet, using publicly available Message Queuing Telemetry Transport (MQTT) services to represent beyond line-of-sight (BLOS) communications pathways
    - Enables future development and experimentation with MLS for securing group communications within manned/unmanned teams
- Conducted preliminary ScanEagle flight testing at Camp Roberts, CA
- Integrated MQ-27A ScanEagle telemetry, position/location information (PLI), and video feeds with Persistent Systems ruggedized tactical communications equipment
- Compared MLS with existing application-layer data encryption schemes, in terms of radiofrequency channel power consumption and Internet Protocol (IP) network bandwidth consumption
- Commenced development of Android Tactical Assault Kit (ATAK) plugin
- Analyzed usability of ATAK for use with MLS to command-and-control UxS

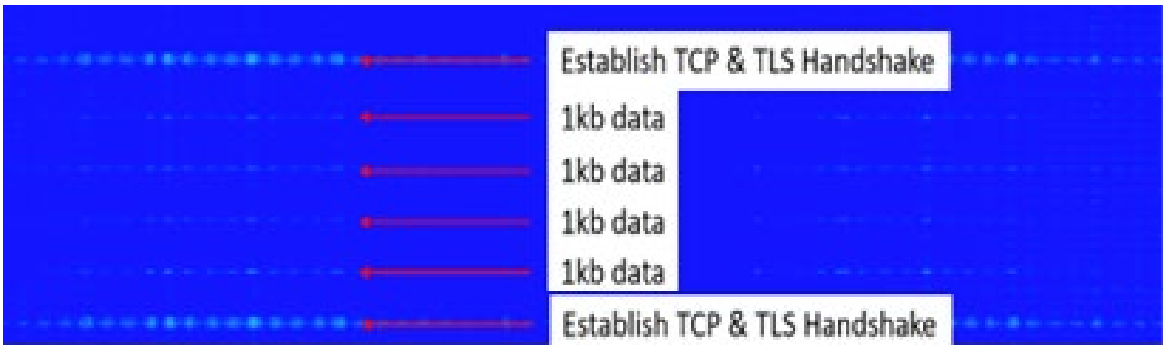

Figure 9: TLS test showing high radio frequency footprint of protocol establishment

Figure 10: MLS test showing low radio frequency detectability for key updates

Figure 11: Radio Frequency comparison test setup

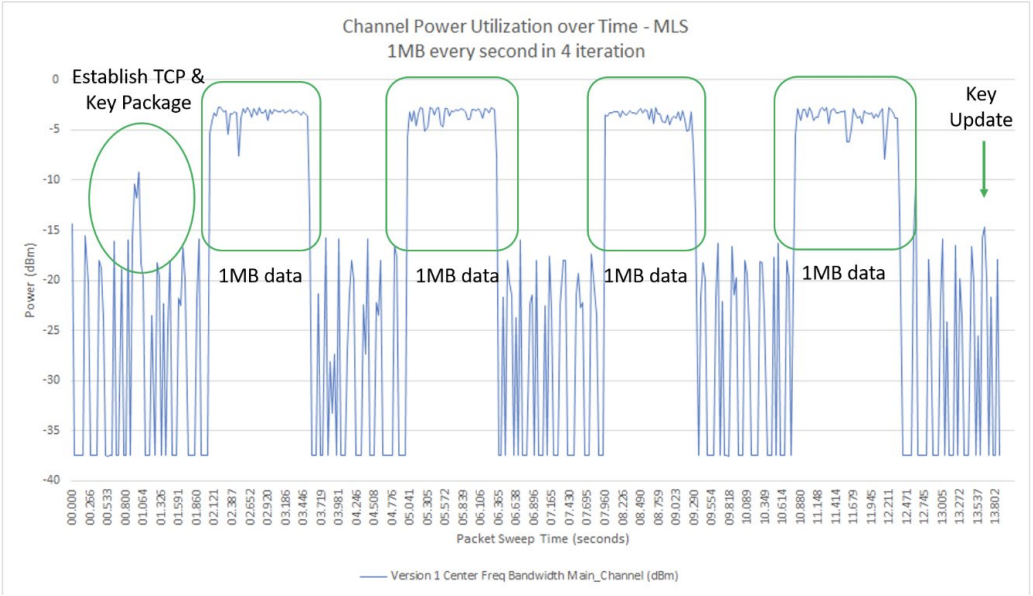

Figure 12

Education:

- C. Yuan, "Power effect of radio frequency on data delivery methods between two autonomous systems," MSc Thesis, Dept. of Computer Science, Naval Postgraduate School, Monterey, CA, Draft.
- Presentation lecture in CS4900 class on research results.

Dissemination:

- Prototype software source code: https://gitlab.nps.edu/jwl/secpubsub
- Presentations (CRUSER, SOF, potential industry transition partners, etc.)
- Lectures and Presentations at NPS
- Connections to the FAA and industry working with USAF on use cases

Collaboration and Partnership:

The Naval Information Warfare Center (NIWC) Atlantic supported on early advisement of power testing and radio frequency detection analysis.

The Naval Special Warfare supported ScanEagle flight testing by providing operators and subject matter experts. In addition, provided relevant user feedback of the software development and applicability of overall objectives for this project.

Transition:

We have been in discussion with JSOC regarding use cases and funding of development and transition. They are currently looking to have a test demo from use for with MPUs in early 2024 with intent to potentially invest in full transition.

An industry company working with the USAF has also expressed interest in getting our work into an international standard for use on UxVs and has asked our team to participate in those standards' development. This would in turn be usable across industry and the DoD.

We have solicited ONR and JSOC for follow-on funding and those requests are currently in review.

E. MULTIROBOT TEMPORAL LOGIC OPTIMAL CONTROL

Participants

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Robert Miske, Operations Research

Ross J. Schuchard, Operations Research

Herbery Jockheck, Operations Research

Benjamin Polzin, Operations Research

Sean Eskew, Operations Research

Kenny Li, Computer Science

Quyen Dang, Computer Science

Major Goals

Development of an approach for integrating consistent system autonomy behaviors into a hierarchical NCS architecture.

Accomplishments:

- Continued development of **B**ehavior **I**ntegration and **O**ptimization for **N**etworked Control System (BION), a NCS hierarchical software that permits distributed control of a collaborative, heterogeneous set of unmanned systems.
- Integrated BION with Model and Simulation Toolbox (MAST). It permits running military scenarios with BION for assessing the mission value of a UxV NCS.
- Developed/Tested the capability for running BION/MAST on the Hamming High Performance Computer (HPC) Cluster.

Education:

- Plunkett, Kyle E., and Anthony Tai. *An Evaluation of Randomized Routing Strategies for Deception in Mobile Networked Control Systems*. Thesis. Monterey, CA; Naval Postgraduate School, 2023.
- Miske, Robert, and Ross J. Schuchard. *Countering Small Unmanned Aircraft Systems with Advanced Data Analysis and Machine Learning*. Thesis. Monterey, CA; Naval Postgraduate School, 2023.
- Jockheck, Herbert W., and Ross J. Schuchard. "Online Optimization to Increase Small Unmanned Aerial Vehicle Surveillance Capacity in Joint Forcible Entry Operations." Thesis. Monterey, CA; Naval Postgraduate School (2023).
- Polzin, Benjamin, and Sean Eskew. "Leveraging Big Data and Machine Learning to Identify and Forecast Factors that Influence the War in Ukraine." Thesis. Monterey, CA; Naval Postgraduate School (2023).
- Li, Kenny. "Unmanned System (UxV) Networked Control System (NCS) Optimization via Reinforcement Learning". Thesis. Monterey, CA; Naval Postgraduate School.
- Dang, Quyen. "Network Control System Optimization: Generalizing Communications Utility by Disruption Tolerant Networking". Thesis. Monterey, CA; Naval Postgraduate School.

Dissemination:

- Peer-reviewed publications.
    - "Routing Against Uncertainty: U.S. Marine Corps Rapid Planning and Logistics Routing Against Uncertainty" (K. Marler, R. Yoshida and C. Vogiatzis). Hybrid Fleet: The Path Forward for Human Machine Teaming (Special Issue). Naval Engineers Journal, March 2023, Volume 135, No. 1. Pages: 115--125.

Transition:

The research is now a fully funded project with the Deputy Assistant Secretary of the Navy for Operational Energy.

F. PERSISTENT SMART ACOUSTIC PROFILER (PSAP)

Participants

Principal Investigator (PI):

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Co-PIs:

Yi Chao (Seatrec Inc)

John Ryan (MBARI)

Students:

LCDR Casey Burgener, METOC Curriculum (373)

Major Goals

This project fully embraces the notions of the Naval Intelligent Autonomous Systems (IAS) Strategy through development of a novel autonomous profiling system that can provide the warfighter with persistent, real-time acoustic characterization of the undersea battlespace. This autonomous system, designated here as the Persistent Smart Acoustic Profiler (PSAP), is designed to provide sustained support over extensive operational periods by furnishing unlimited system power through an ingenious energy-harvesting process that extracts energy directly from ocean thermal gradients through solid-to-liquid phase transition. The profiler also employs smart hydrophone technology that distills raw acoustic data into short information messages that can be readily transmitted to a distant command center (land or sea based). Two-way communication allows remote operators to adjust mission parameters as needed based on changes in mission needs and/or environmental conditions. Figure 1 provides an overview of the PSAP concept of operations. PSAPs can be used as independent units or combined into a network providing wide-area coverage of the maritime battlespace. These systems enable an innovative concept of operations that can support a broad spectrum of naval undersea warfare (USW), intelligence surveillance and reconnaissance (ISR) and battlespace awareness (BA) missions.

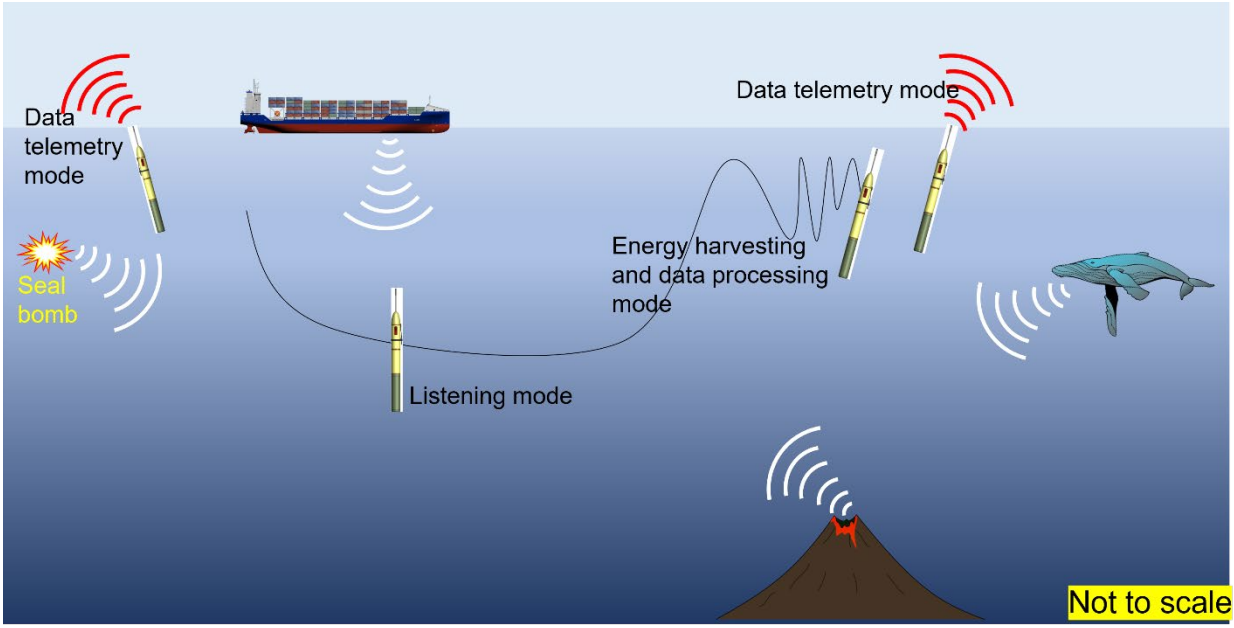

Figure 13: PSAP concept of operations combine a unique energy-harvesting buoyancy engine (Seatrec) and smart hydrophone technology (Ocean Sonics) to provide the warfighter with persistent maritime surveillance.

Accomplishments:

This year, the project co-PIs continued to meet to discuss issues related to the development of the Persistent Smart Acoustic Profiler (PSAP) and lay out a test plan. By summer, PSAP had matured into a working platform ready for sea trials. Seatrec engineers integrated an Ocean Sonics RB9 icListen Smart hydrophone and an RBR Concerto CTD instrument on the platform. An overnight 24-hour wet-test was conducted in Monterey Bay on 17-18 Aug 2023 from RV Fulmar, the research vessel operated by the Monterey Bay National Marine Sanctuary (MBNMS). The PSAP is a "2-person portable" system that is sufficiently light enough to hand-deploy off the stern of the RV Fulmar (Figure 14). The deployment site was selected to be directly over the Monterey Bay Aquarium Research Institute (MBARI) MARS Cabled Observatory, which is located at Smooth Ridge at 900m depth on the north wall of Monterey Canyon. The MARS observatory has an identical Ocean Sonics RB9 icListen hydrophone connected to it which sends data ashore in real time. This enabled us to make a direct comparison of the soundscape observed by both hydrophones collected simultaneously at nearly the same locations (Figure 14).

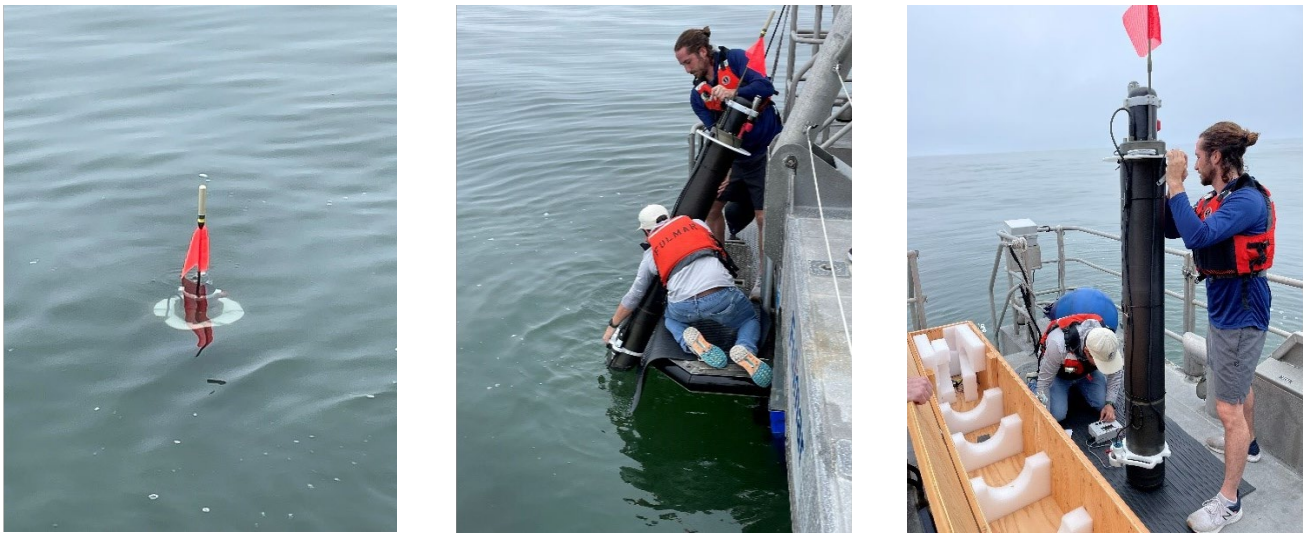

Figure 14: (From L to R) Final preparations for the initial PSAP deployment; Hand-deployed off stern of RV Fulmar; PSAP at surface just prior to first dive

The initial test was a remarkable success. The PSAP was programmed to make three 8-hour dives to 400m depth over the 24-hour period. It successfully completed these dives as scheduled. Prior to deployment, the system was ballasted for buoyancy conditions expected in Monterey Bay. On the first dive, the PSAP overshot the target depth by a few meters and had to make a slight adjustment with its buoyancy pump to bring the system to precisely 400m, where it remained in listening mode until the next planned surfacing. On the subsequent dives, PSAP learned from feedback from its previous dive just how much fluid it needed to pump to reach the target depth with adjustments. By the third dive, the system reached its target depth with no adjustment required after the initial pump at the surface. Because buoyancy pumping is a noisy operation, it masks any sounds received from the soundscape. By reducing the interfering adjustments needed to reach the target depth, the acoustic data collected is much cleaner.

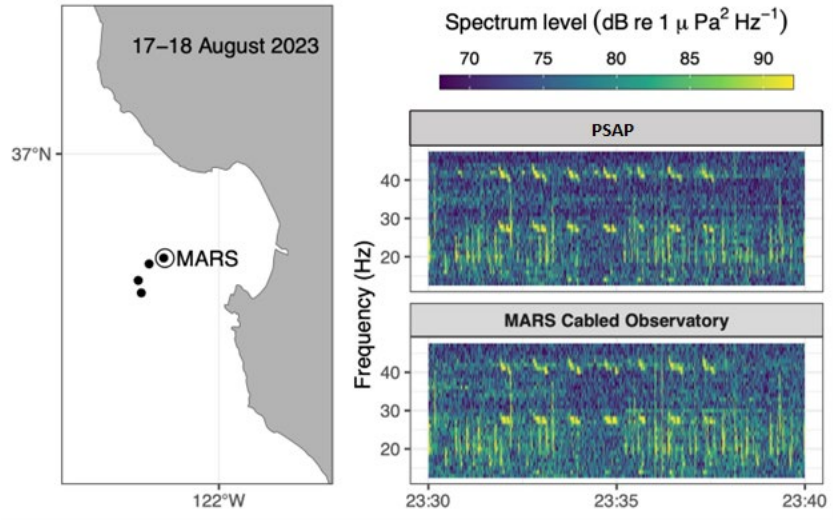

Figure 15: (left) Map showing the location of the MARS cabled observatory (open circle) and the surfacing locations of the PSAP (back dots) which was initially deployed over MARS. (right) A comparison of 10-minutes of spectral data from the PSAP (top) to the MARS hydrophone (bottom). At the time of the recording the PSAP was approximately 3 km west of MARS. Reception of fin whale calls at 20 Hz and blue whale calls at 28Hz and 42Hz received at both hydrophones is nearly identical.

On each PSAP dive, Seatrec's unique energy harvesting process went into operation. The phase-change material (PCM) freezes when the PSAP dives below the thermocline and upon surfacing, the PCM remelts and expands, producing high hydraulic pressure to power a generator that recharges the system battery. Under the conditions of the test day in Monterey Bay, this produced ~6kJ of energy per dive which is sufficient to maintain a limitless power supply for the PSAP be deployed forever, theoretically. **This makes PSAP distinct among soundscape monitoring systems. Moored systems or glider-based systems are battery-limited and must be recovered to refresh their data collection capability or they are lost.**

A comparison of 10-minutes of spectral data from the PSAP to the MARS hydrophone is shown in Figure 3. At the time of the recording, the PSAP was approximately 3 km west of the MARS observatory on its first dive. The MARS hydrophone was at 900m depth and the PSAP was at its target dive depth of 400m. Given the acoustic transparency of low frequency sound, we expected the response to sound in this band to be similar. Fortunately, fin whales and blue whales were vocalizing at this time and the reception of fin whale calls at 20 Hz and blue whale calls at 28Hz and 42Hz received at both hydrophones is nearly identical.

During this test, we communicated with the PSAP from shore via Iridium satellite, however only location information, engineering data and command/control information were tested. Data collected through hydrophone was stored on board. For this at sea test, we sampled at the hydrophone's maximum sampling rate (512 kHz) enabling acoustic resolution over the 0-240 kHz frequency band. There are few no known natural sources in Monterey Bay that produce sound at those frequencies, however we did hear the 38 kHz signal from an echosounder connected to the MARS observatory. In an upcoming test, passing acoustic and environmental information from PSAP to shore will be tested. PSAP has an onboard Linux computer that will be handing a number of processing and communication tasks, enabling valuable soundscape data to be received at shore stations in near real time. This enforces the advantage of not needing to recover the PSAP and send it on very long extended missions. The onboard computing capability also offers the ability to add several detectors to the system tailored to future applications in a variety of research experiments and naval exercises.

With CRUSER support, PSAP has gone from a concept to a reality. Its remote sensing capability can be used to address a variety of research questions and support a broad spectrum of naval undersea warfare (USW), intelligence surveillance and reconnaissance (ISR) and battlespace awareness (BA) missions.

Education:

- PSAP offers numerous opportunities for student thesis research. In addition to evaluating and optimizing the three fundamental functions described above, student research efforts can focus on expanded capability such as using multiple PSAPs to work as a sparse array for wide-area surveillance, improve its library of detection algorithms, add steering capability by using predicted currents, add additional sensors that can improve USW-related capability, investigate energy efficiencies that support integration of additional sensors while minimize energy-harvesting demand.
- In addition to supporting student research, PSAP can be used in support of applied courses in oceanography such as Tactical Oceanography and Descriptive Oceanography as well as courses in robotics that address remote piloting and controls of undersea autonomous vehicles. PSAP data can be applied in courses that teach development of

auto-detection methods, including applications of AI/ML methods to characterize signals of interest.

Dissemination:

Based on the results of the first tests described in this summary, a paper published in JASA Express Letters is in progress. We expect to use PSAP for its remote sensing capability in several upcoming projects including Synchro, Task Force Ocean and Monitoring Rice's Whale in the Gulf of Mexico. There are several other projects the PSAP team is participating in that are expected to result in the development of similar platforms with slightly different capabilities. PSAP results are paving the way to speeding their development.

We anticipate that PSAP will offer many opportunities for NPS student research particularly in support of the USW (525) and METOC (373) curricula. There is a need to distill raw acoustic data into operationally impactful information on board the platform using a low power computer, which offers the opportunity for implementing new algorithms (some, perhaps, AI/ML based) to get critical information from remote sites in near real time in support of research in underwater acoustics, soundscape analysis and battlespace awareness.

Collaboration and Partnership:

The concept for this project developed from conversations with Dr Yi Chao following a seminar he presented at NPS in July 2021. Dr Chao is a renown physical oceanographer and ocean modeler, formerly at NASA's JPL and now CEO (and founder) of Seatrec Inc, a spinoff from CalTech to commercialize the patented energy-harvesting technology. During his visit to Monterey, Dr Chao also met with Dr John Ryan, a research scientist at MBARI who NPS has collaborated with in various projects on soundscape characterization and use of passive acoustic data in marine mammal ecology research. Recognizing the potential that development of a long-endurance autonomous ocean/acoustic sensing platform can contribute to soundscape monitoring, marine mammal ecology and numerous naval applications, the three of us submitted a joint proposal to the CRUSER SEED Call for Proposals that was well-aligned with the DoN IAS Strategy.

Transition:

This effort has many applications to both civilian and naval research and operations. The unique energy-harvesting technology enables PSAP to overcome power limitations suffered by most small underwater autonomous systems, resulting in unprecedented endurance performance. As the system is matured and performance documented through field testing supporting student research, we intend to further demonstrate and advance system capability with additional support. At the appropriate time, we will socialize PSAP with potential sponsors at ONR, N45-LMR, UWDC and NOAA.

G. COLLABORATIVE HYPER-ENABLED OPERATIONS IN CONTESTED ENVIRONMENTS (CHOICE)

Participants

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Students:

Maj. Juncun Su, Singapore Air Force

Major Goals

The objectives of the proposed work included both theoretical and experimental components. On the theoretical side we planned to address Distributed Time-Critical Cooperative Trajectory Generation Under Severe Operational Constraints: path planning that guarantees simultaneous arrival of the USVs must account for the absence of GPS (i.e. a position sensor with consistent error bounds), severe communication constraints and rapidly updated maps of the landing site, unexpected obstacles as well as waves and currents in the littoral zone. In addition, new results are required to address Time-critical cooperative path following in the presence of intermittent/range limited communications: develop new formalism to explicitly accounts for such severe communication constraints. Support the theoretical developments with experimental work.

Accomplishments:

- New collision avoidance algorithm in the absence of GPS with limited or no communications
- New time critical path following framework that accounts for limited communications
- New time critical path following framework using Even Triggered communications
- New Attitude and Heading Reference System (AHARS) flown on ScanEagle
- New Secondary Controller/Back Seat Driver (NVIDIA TX2) flown on ScanEagle

Education:

Juncun Su, “SIM-1 UAS: A FRAMEWORK FOR RAPID PROTOTYPING OF MATLAB DEVELOPED FLIGHT TEST CODE,” NPS MS Thesis, Fall 2023

Dissemination:

Cichella, V.; Kaminer, I. Coordinated Vision-Based Tracking by Multiple Unmanned Vehicles. *Drones* 2023, *7*, 177. https://doi.org/10.3390/drones7030177

T. Tsatsanifos, A. H. Clark, C. Walton, I. Kaminer and Q. Gong, "Modeling Large-Scale Adversarial Swarm Engagements using Optimal Control," submitted to IEEE Journal of Aerospace and Electronics.

H. Kang, I. Kaminer, V. Cichella, and N. Hovakimyan, “Coordinated Path Following of UAVs over Time-Varying Digraphs Connected in an Integral Sense,” submitted for presentation at 2024 American Control Conference.

Collaboration and Partnership

We have continued collaborating with Prof. Cichella and his student C. Tabasso at the University of Iowa, Prof. Hovakimyan at the University of Illinois Urbana Champaign as well as Prof Walton at UT at San Antonio and Prof Qi at UCSC. These collaborations resulted in the Drones publication and the manuscripts submitted to 2024 American Control Conference and IEEE Transactions on Aerospace and Electronics.

Naval Special Warfare (NSW) supported flight testing by providing operators and subject matter experts. In addition, NSW provided relevant user feedback of the new hardware development and applicability of overall objectives for this project.

Transition

At the invitation of Mr. Steinberg, ONR-351, we have resubmitted a proposal, “Autonomous Mapping and Landing in a GPS-denied Environment Proposal,” to ONR-351.

H. MAD-CAT: MODULAR AUTONOMOUS DRONE-CONFIGURABLE AERO TARGET

Participants

Principal Investigator (PI):

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Collaborators:

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Students:

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Rebecca Kennedy, 299

Felix Fagan, 299

See appendix for further information

I. MECHANICAL DESIGN AND COMSOL ANALYSIS OF ARCHIMEDES-FORCE QUIESCENT UUVS FOR LARGE-SCALE DISTRIBUTED OFFENSIVE MINE OPERATIONS

Participants

Principal Investigator (PI):

Emil Kartalov <epkartal@nps.edu>

See appendix for further information

J. HYBRID SWARM ATTACKS IN CONTESTED ENVIRONMENTS

Participants

Principal Investigator (PI):

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Violet Mwaffo, mwaffo@usna.edu, U.S. Naval Academy

Matt Feemster, feemster@usna.edu, U.S. Naval Academy

CDR Paul Frontera, frontera@usna.edu, U.S. Naval Academy

Students:

ENS Jennifer Nguyen, Curriculum 570

LT Kyle Goncz, Curriculum 570

LT Kris Rodriguez, Curriculum 570

Major Goals

This project continued an unmanned surface vessel (USV) research collaboration between NPS and USNA that began in 2022. The effort had two main focus areas. First, NPS developed algorithms for a sub-team of USVs to conduct coordinated attacks on specific objectives as members of a large multi-domain swarm. NPS worked with engineers from NSWC-Carderock to integrate these algorithms on existing hardware, software, and communications architectures used at ONR's annual robotics force-on-force experiment. This experiment is an important venue for developing robotics capabilities and tactics for human operators to employ in realistic operational scenarios.

Second, NPS and USNA faculty investigated algorithms to achieve reliable formation control for a team of USVs when 1) the team is comprised of heterogeneous vessels with different dynamics and control characteristics; and 2) radio communications may not be available for coordination. To address the first challenge, NPS and USNA exchanged algorithms and vehicle control software so an NPS thesis student could simulate the dissimilar vessels used at both institutions and assess algorithm suitability. To address the second challenge, researchers explored the use of

low-cost, commercially available OAK DepthAI cameras for perception of friendly vessels and obstacles.

Accomplishments:

- Procured two Mokai motor-driven kayaks for NPS USV research and education.
- Adopted the same hardware, software, communications, and operator interfaces utilized by NSWC-Carderock to ensure that NPS USVs can interoperate with other Mokai and trained operators at ONR field experiments.
- Implemented NPS coordinated path following (CPF) for aggressive trajectories designed to increase survivability and/or lethality against adversarial forces.
- Demonstrated nonlinear trajectory generation and path following on the NPS Mokai USVs.
- Based on warfighter feedback during pre-event training, NPS added an OAK stereo camera and Persistent Systems MPU5 mobile ad-hoc network (MANET) radio for streaming first-person view video to a wearable display unit. This allowed operators to conduct teleoperated attacks.
- Meetings with faculty and students at USNA facilitated a Bowman Scholar's ability to build upon their Bowman research project at USNA via a masters thesis at NPS.
- Conducted local follow-on experiments at Lake San Antonio to collect OAK camera video datasets supporting thesis on USV perception by LT Goncz.

Education:

K. Delanoy, "Swarm tactics using aggressive trajectory generation and optimal path planning with USVs," Master's thesis, Dept. of Mech. and Aero. Eng., Naval Postgraduate School, Monterey, CA, 2023.

J. T. Nguyen, "Exploration of formation control algorithms for unmanned surface vehicles," Master's thesis, Dept. of Mech. and Aero. Eng., Naval Postgraduate School, Monterey, CA, 2023.

AE4850 Dynamic Optimization: ENS Nguyen used USV dynamic models developed for this research for their final project.

ME4824 Applications of Deep Learning for Military Systems: ENS Nguyen, LT Goncz, and LT Rodriguez utilized scenarios and/or experimental data from Mokai experiments for their final projects.

Dissemination:

The following paper has been submitted to the American Control Conference:
Violet Mwaffo, Paul Frontera, Matthew Feemster & Sean Kragelund. "Identification of the Stochastic Dynamic of a Small Catamaran Surface Vessel," submitted.

Collaboration and Partnership:

In addition to this research partnership with USNA, NPS has been integrated into ONR Code 34's research portfolio. In this role, NPS has been closely collaborating with NSWC-Carderock. This year, NPS researchers traveled to ONR land-based experiments to facilitate new collaborations with NSWC-Dahlgren and NSWC-Panama City, as well as John Hopkins Applied Physics Lab and several small companies developing artificial intelligence applications for ONR. However, NPS has agreed only to disseminate details of this work to DoD and U.S. DoD Contractors (DISTRIBUTION D), at the sponsor's request.

Transition:

NPS obtained $80K of matching funds from ONR in 2023, and ONR has agreed to transition this CRUSER research to full ONR funding in 2024.

K. DEEP NEURAL NETWORK STATE ESTIMATION AND CONTROL IN GPS AND RADIO DENIED ENVIRONMENTS

Participants

Principal Investigator (PI):

Violet Mwaffo, mwaffo@usna.edu, U.S. Naval Academy

Co-PIs:

CDR Paul Frontera, frontera@usna.edu, U.S. Naval Academy,

Matt Feemster feemster@usna.edu, U.S. Naval Academy

Sean Kragelund, spkragel@nps.edu, Naval Postgraduate School

Students:

MIDN 1/C Chelsey Washington (current Bowman Scholar)

Major Goals

Unmanned Vehicles (UVs) have shown numerous applications for the Navy in missions encompassing intelligence, surveillance, reconnaissance to tactical strike, and formation escort. Their operation currently requires a significant amount of data exchanged through radio communication, remote relay transmission or command stations, and GPS navigation systems. In contested electromagnetic environments, these traditional means of communication might be altered or undermined requiring novel approaches that will extend mission capabilities and improve ability to conduct operations in denied or contested water and airspace. The primary technical objective of this proposal will focus on the design of a state estimation and control algorithms for autonomous coordination of multi vehicles systems using deep neural networks. An additional objective will focus on the integration of the recently acquired, high-speed Apache3 unmanned surface vessel (USV) within USNA's existing fleet.

Accomplishments:

A deep neural network (DNN) framework has been explored to enhance perception capabilities. This framework consisted of two main subsystems: a 3D Object Tracking Subsystem, which uses an OAK-Camera on a pan-tilt servo arm to track objects within a 180-degree view, and a 360-Degree View Coverage Subsystem, comprising multiple OAK-Cameras mounted on a frame for full spatial coverage. Both subsystems were powered by a DNN trained on maritime environment images, optimized for processing on the OAk-Camera computer board. Key functionalities

included the first subsystem's ability to determine 3D positions of objects (see Figure 1) within a 180-degree range, and the second subsystem's extension of this to a 360-degree range, also integrating Spatial AI for depth perception and object localization.

Figure 16: 3D position of a Kingfisher USV detected by the DNN model in a video recorded near College Creek

Future improvements will focus on Spatial Depth AI, combining AI with depth data for enhanced 3D positioning, obstacle detection, and increased spatial awareness. These developments mark significant progress in AI and depth perception integration. The developed system will also be tested onboard a USV in a maritime environment to evaluate its performance notably for providing relative positioning data to control the operation of multiple USVs.

- Operated Apach3 USV in teleoperated mode in College Creek.
- Developed Python software to acquire sensor data (wirelessly) from Apache3 USV (GPS, inertial, depth, and forward-looking radar measurements).
- Developed Python integration software to command Apache3 thruster levels.
- Performed initial experimentation to identify Apache3 system parameters (*e.g.*, drag, *etc*.)*.
- Designed and implemented closed-loop speed and heading control algorithms on Apache3 USV*.

- Simultaneously commanded both the Apache3 and Kingfisher USV (see Figure 2) on the same wireless network*.

* These accomplishments were performed in part by MIDN 1/C Chelsey Washington in support of her current Bowman research project.

Figure 17: Apache3 (left) and Kingfisher (right)USV in College Creek

Education:

USNA course EW413 Digital Control Systems: midshipmen were tasked with the design and integration of a low-level heading control algorithm for unmanned surface vessels.

Dissemination:

The following paper is the based-on work performed with 2022 CRUSER funding support:

Paul Frontera, Matthew Feemster, Jennifer Nguyen, "Application of Rigid Formation Control to marine vessels", *Ocean Engineering*, vol. 277, 2023.

Collaboration and Partnership:

Over the funding period, USNA investigators have been in discussions with Dr. Marcio de De Queiroz (mdeque1@lsu.edu) and Dr. Cortina Barbalata (cbarbalata@lsu.edu) from Louisiana

State University to combine USNA's fleet of surface vessels (Apache3 and Kingfisher) with LSU's underwater vehicles to create a fieldable heterogeneous formation. The results of these discussions may lead to future funding opportunities between USNA and LSU (and possibly NPS).

Transition:

Efforts are underway between USNA investigators Mwaffo, Feemster, and Frontera and Professor Sean Kragelund of the Naval Postgraduate School in the preparation of an Office of Naval Research white paper entitled "*Cooperative Formations using Dissimilar Marine Vessels.*" The proposed work will build upon the two previously funded CRUSER projects by focusing on utilizing vessels with widely dissimilar operating characteristics (such as the above Apache3 and Kingfisher vessels) in a cohesive formation. Expected submission is early January 2024.

L. ONBOARD AUTONOMY FOR EXCEPTION HANDLING IN UXS OPERATIONS

Participants

Principal Investigator (PI):

Dr. Mollie McGuire <mrmcguir@nps.edu>

Co-PIs:

Aurelio Monarrez <amonarre@nps.edu>

Major Goals

The objective of the proposed research is to learn about an operator's ability to manage multiple UxVs in multiple domains. The long-term goal of this line of research is to understand the limitations of one operator managing multiple UxVs with the aim to build AI to effectively assist.

If the future of command and control is multi UxV operations by one operator, then the parameters of what the operator can handle need to be assessed.
Experimentation was conducted with simulators representing the control of multi-domain UxVs. The number of UAVs was systematically varied so for elements to be examined for their added difficulties, while keeping a UUV

Accomplishments:

- Experimentation was conducted with trained ScanEagle operators. Participants managed multiple ScanEagles in simulation with one UUV. The difficulty of the contexts varied with errors introduced on each of the four sessions.
- One of the most common operator errors in the management of multiple UAVs is that they broke airspace. This common error is a good example of how onboard AI can assist in maintaining operations when an operator is managing multiple UxVs.
- While the UUV asset was relatively hands off from a management aspect, it did add to the attentional resource burden. The eye tracking that was used showed that even after the UUV was out of play (stuck in kelp) the operator still spent some time scanning to that

screen. The addition of even a mostly hands off asset increased the attentional and cognitive load of the operator, taking the attention away from the more complex assets.

Education

We were not successful in student recruitment, and do not have anything to report on this aspect.

Dissemination

Results will be compiled across the entire, multi-year research effort and submitted to the appropriate conference, HICSS or similar.

Collaboration and Partnership

Naval Special Warfare supported UxS simulation testing by providing operators and subject matter experts. In addition, provided relevant user feedback of the test plan and applicability of overall objectives for this project. Naval Special Warfare Command provided letter of support for this project.

Transition

Have been in communication with Naval Special Warfare and Office of the Secretary of Defense about potential sponsorship. In addition, Naval Special Warfare has agreed to continue providing letters of support and operator participation.

M. SUAS-BASED REMOTE SENSING OF SURFACE WAVES AND BREAKING USING AN EO/IR CAMERA SYSTEM

Participants

Principal Investigator (PI):

David Ortiz-Suslow, dortizsu@nps.edu

Senior Personnel:

Jesus Ruiz-Plancarte (JRP)

Major Goals

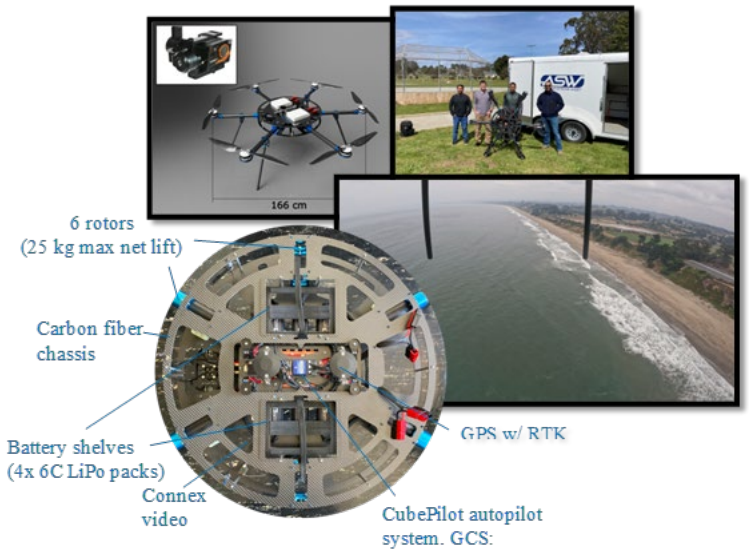

Figure 18: Clockwise from upper left: schematic of HLM along with inset of WIRIS Pro Sc EO/IR camera with gimbal, which has been successfully integrated into HLM platform; picture of initial manufacturer-provided training at HLM training delivery during spring 2023; GoPro image from first over-water flight of HLM taken in fall of 202; view of HLM body taken in the laboratory with major system components labeled.

The goal of this project was to develop a sUAS-based remote sensing platform for measuring ocean surface waves and breaking in the coastal area to improve our understanding of these phenomena. The aim of this work is to improve the underlying physical relationships used to parameterize role surface waves play in the atmosphere-ocean coupled domain. This will enhance environmental forecasting for weather and climate processes, as well as holds implications of electromagnetic energy propagation in the marine atmosphere because surface waves not only disrupt atmospheric turbulence structure, when they break, they eject marine aerosols that scatter and attenuate EM signals and energy. The FY23 project builds on previous CRUSER funding to support the acquisition and initial integration of the sensor package.

The major goals for this PoP were to: (1) receive delivery of the Aerosystems West Heavy Lift Multirotor (HLM), (2) augment payload integration with RTK GPS and real-time video transmission, (3) conduct initial field testing and data collection in nearby coastal area using HLM and WIRIS EO/IR camera.

Accomplishments:

- Drone/payload delivered and integrated Spring,
- Initial training and test flights in Spring,
- Additional acquisition and integration to utilize RTK GPS and video transmission augments to the drone system,
- 2 successful flight missions from a coastal site, including over-ocean flying and imaging,
- Initial analysis of platform performance using high-rate system log data,
- Presentation of initial platform development at major defense technology conference,
- Pending presentation at major meteorology and atmospheric science conference in early 2024.

Dissemination:

Ortiz-Suslow, D. G. (2023): The Impact of Ocean Surface Waves and Breaking on the Atmospheric Surface Layer. 2023 Defense TechConnect Innovation Summit & Expo, November 2023. National Harbor, Maryland, USA.

(*accepted, up-coming*) Ortiz-Suslow, D. G., & J. Ruiz-Plancarte (2024): Observing Breaking Waves Using EO/IR Remote Sensing from a Rotary-Wing UAV. 24th Symposium on Meteorological Observation and Instrumentation, AMS 104th Annual Meeting, January 28 – February 1 2024. Baltimore, MD, USA.

Collaboration and Partnership:

Established new collaboration with JRP (newly promoted Research Assistant Professor in Meteorology) on this project,

Collaborated with Prof. Mara Orescanin on joint field testing to leverage UAS expertise on campus to better transition this new capability into a viable research platform for the PI to pursue further research study.

Transition:

Opportunities to garner extramural funding using this drone platform will continue to be explored, as well as using this to support student thesis research.

N. ORCHESTRATED AUTONOMOUS MARITIME COLLECTION

Orchestrated Autonomous Maritime Collection

Participants

Principal Investigator (PI):

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Co-PIs also in the ECE Department, Center for MultiINT Research (CMIS):

Dr. Jihane Mimih jmimih@nps.edu

Prof. Ed Waltz edward.waltz@nps.edu

Students:

LT Conor P. Murtha, Strategy & Space Operations Curricula 696

Major Goals

Objective: Demonstrate by analysis and modeling, the feasibility of integrating three classes of autonomous vehicles (Space-Surface-Air) to enhance the detection, warning, identification, and custody of maritime surface vessels. Our objective addresses the Navy need for "Intelligent machines that can adapt in unstructured environments, at machine speed, and given overwhelming data … and are attritable when necessary." [1] The objective is to enhance the applicability of short range UAS-UAV platforms to contribute to long-range cooperative engagement.

Approach: We developed and evaluated alternative approaches (Table below) to integrate autonomous unmanned surface vessels (USV) or air vehicles (UAV) and space-based sensor collection (Commercial EO and SAR) to enhance maritime domain awareness and cooperative engagement. Automated vessel tracking, cross-cueing, handoff, and surveillance were evaluated to determine feasibility of USV-UAV-Space coordination.

Orchestration Mode	Description
1. Space Cue to Surface Fusion for Custody	Space collection tracks suspicious vessels and cues autonomous vessels to monitor or pursue surface vessel targets of interest (VOI) that are approaching, or near to UAV/USV. Space-observed vessels in designated area coverage provide context awareness to cue UAV's and USV's surface vessels to provide close-in ISR.

2. Air-Surface Cue to space	USV and UAV detect and ID surface threats that traverse through coverage; these platforms cue the space constellation to acquire and track vessels.
3. Combined Tracking	Full coordination between space and USV/UAV to sustain track and enable cooperative engagement.

This approach integrates the elements of Intelligence Autonomous Systems (IAS) at machine speed to orchestrate and focus collection for maritime domain awareness:

- Unmanned Systems –UAV's and USV's provide surface target reporting and receive cues from other air, surface, and space sources for fusion to enable adaptation.
- Autonomy – The cross-cueing process is autonomous – maximizing the information on surface ship targets to stationary, station-keeping (SeaDrone USV) and surface vessels (e.g. MAST-13 USV) to autonomously carry out their missions.
- Artificial Intelligence - The orchestration system 1) applies machine learned models of vessels, their behaviors, and characteristics to identify targets, 2) applies AI sensemaking to fuse ship information and predict next-collection opportunities, and 3) recommend coordinated collection orchestration to maximize the fleet's situation awareness.

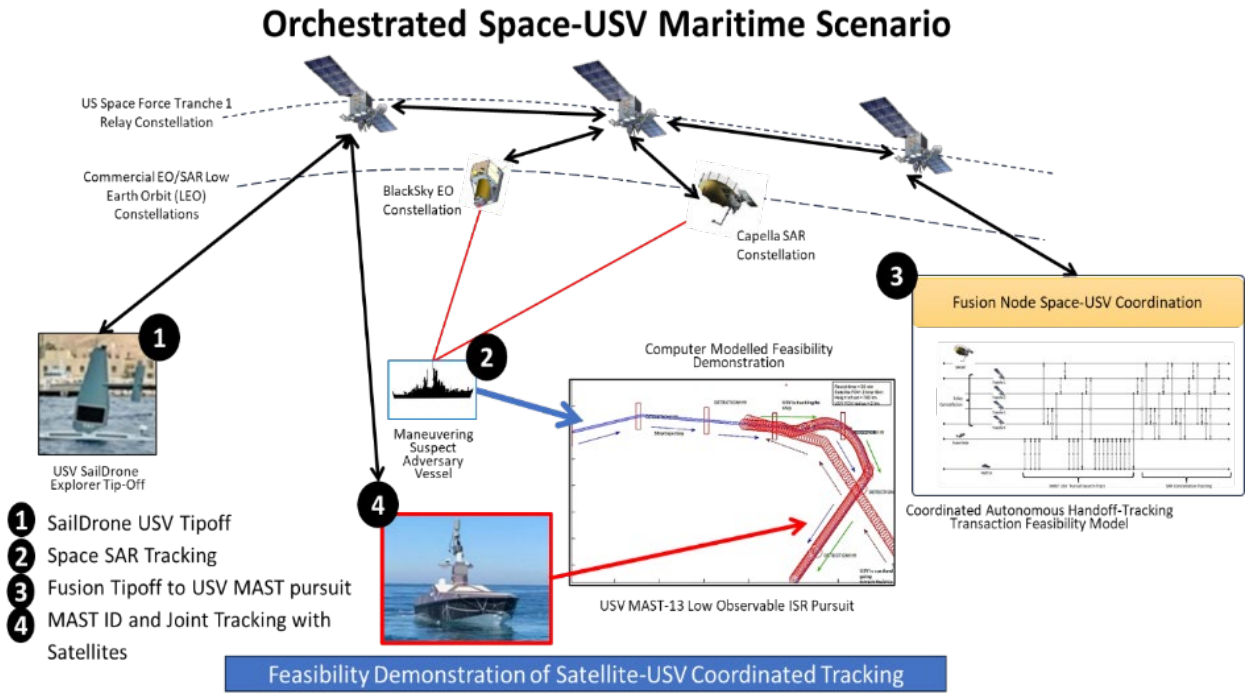

Figure 19: Orchestrating Autonomous Space and Surface Collectors

Figure 17 illustrates the scenario we modelled to demonstrate feasibility the Space-USV concept of a realistic scenario for the combined case. A stationary SailDrone provides a tip for a SAR satellite constellation to acquire and track a maneuvering vessel, and then handoff the track to a MAST USV to pursue the vessel and provide close-in ISR to enable cooperative engagement. Our study approach applied computer modeling to verify that the sequence of computer network transactions can be completed, and that the satellites and USV's can maintain a viable track of the maneuvering vehicle.

Accomplishments:

We have demonstrated the feasibility of employing a space asset and an autonomous vehicle such as a UAV or USV to work together to maintain custody of a maritime target to enable cooperative engagement (Figure 18).

This is accomplished through the following steps:

1. The space asset (a small commercial satellite) detects a suspicious vessel. However, it is not always possible to identify the vessel due to a wide range of reasons such as resolution limitations, cloud cover, atmospheric interference, sun angle, sensor limitations, and signal processing limitations.
2. The smallsat takes advantage of using the nearby available autonomous assets (UAV or USV) and sends them a tip so that the closest one will proceed to intercept the approaching vessel of interest and identify it and to maintain covert custody at a distance.
3. The autonomous asset performs covert reconnaissance using passive electro-optical or signal emission identification to identify the adversary's vessel.
4. The autonomous asset follows the vessel within the range to maintain and report track to support remote vessels that may engage the target by cooperative engagement.

In this project, we assume that autonomous vessels enable the satellite to retain custody of the vessel when the satellite fails to detect the object. We assume that when the satellite is unable to identify the object, it can transmit a query to the autonomous vessel to provide the location and direction of the ship. This information assists the satellite in adjusting its field of view to effectively detect the vessel.

While the autonomous vessel maintains custody of the vessel, it can guide the satellite to look in the appropriate location, not necessarily during the revisit time when the satellite initially missed the object but in future revisit times. Figure 2 illustrates one scenario we modelled and the results that verify feasibility of the CONOP; the satellite constellation revisits the area every 30-45 minutes and tracks a suspicious vessel before tipping a USV to pursue and intercept the vessel to positively identify it.

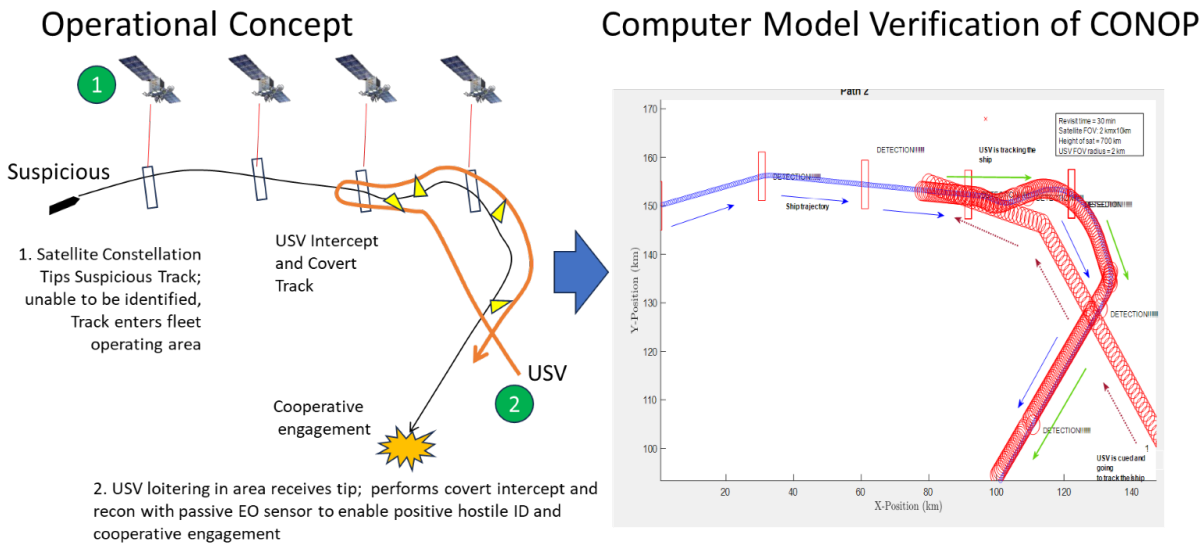

Figure 20: Space to UAV/USV Handoff Scenario

Simulation and Results: We modeled the transactions between the satellites, a fusion node coordinating the tracking and handoff process, and the USV to enable estimation of communication latency, and transaction margin (Figure 19) to assess the feasibility of performing the complex sequence of data exchanges.

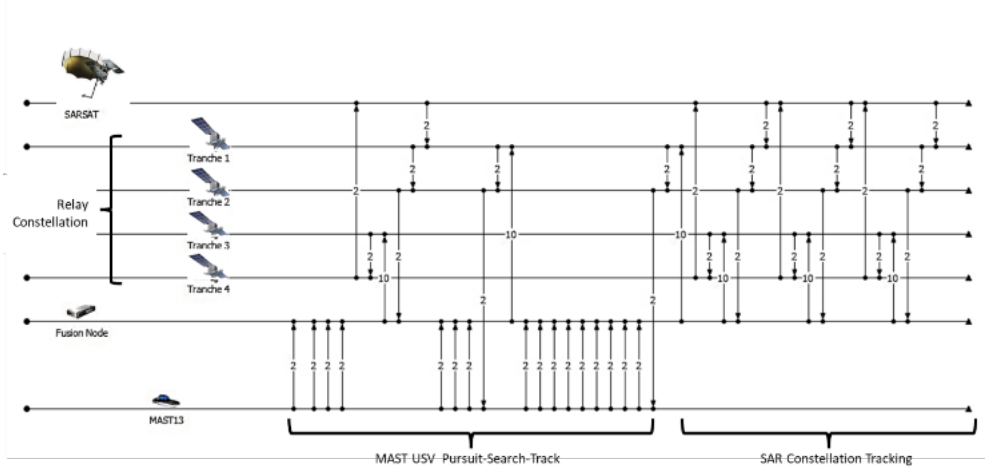

Figure 21: Network transactions in the SAR-to-UAS handoff Scenario

We simulated a suspicious ship moving along two different trajectories within an area spanning 200 km by 200 km. The two trajectories differ in the maneuvering of the ships and the times those maneuvers occur. This distinction is crucial because the satellite relies on the ship's current location, speed, and direction to project its next observation point. When the vessel undergoes a significant maneuver resulting in a substantial change in direction, it impacts the success of the mission, specifically custody maintenance. We performed a sensitivity analysis, investigating the impact of following on the success of an ISR mission focused on maintaining custody of a ship of interest: 1) Effect of satellite field of view (FOV), 2) Effect of changing the revisit rate of the satellite, and 3) Effect of changing autonomous vessel sensor FOV radius.

Education:

Thesis in Progress "Space-Surface-Air targeting Coordination for DMO"; LT Conor P. Murtha

EN3010 "Introduction to Robotics and Energy Systems" coursework included the analysis of Space, UAV and UAS systems modeled in this project.

Dissemination:

Waltz, E., Mimih, J., and Stork, K., *Analysis of Distributed Data Fusion in DMO Surface Warfare. Proc. of DoD National Security Sensor and Data Fusion*, Paper Unclassified, Nov. 2023. This

paper reported on a portion of the study that dealt with tracking feasibility from P-LEO, shared with analysis under a separate study for different sensing systems.

Mimih, J. and Waltz, E., *Space-to-USV Orchestrated Autonomous Maritime Collection*, Naval Postgraduate School, December 2023, Results of this study disseminated to Naval Information Warfare Center-Pacific (NIWC-PAC)

Collaboration and Partnership:

We have collaborated with the Naval Information Warfare Center-Pacific (NIWC-PAC) to develop and assess this concept. Our collaboration is with the US Navy Multi-INT Fusion and Correlation Technology Lead (SSTM), Mr. Mark Owen. Our collaboration included a discussion of the concepts of this study and the metrics to assess its feasibility, we briefed Mr. Owen on our ongoing research in this area who in turn briefed interested Pentagon personnel on 04 December 2023. We also discussed our work with Paul Millhouse, a Senior Director, US Government Business Development at Maxar Technologies which will be launching the LEGION satellite constellation of imaging satellites in 2024 and this is a potential experiment for the constellation. Maxar is the NWIC-PAC contractor for commercial satellite maritime data fusion experiments.

Transition:

We believe a follow-on detailed design study is required before an experiment that will be conducted with NWIC and Task Force 59. Our efforts to attract reimbursable support have included a continued collaboration with NIWC-PAC to lead to a proposal in FY 24, related development of related P-LEO concepts via an NRP project to further mature concepts, and discussions with Maxar Technologies that may lead to a joint study.

O. TRAFFIC ANOMALY DETECTION AND ANALYSIS FOR 5G ENABLED AUTONOMOUS VEHICLE SYSTEMS

Participants

Principal Investigator (PI):

Dr. Preetha Thulasiraman <pthulas1@nps.edu>

Students:

Maj. Kaijian Lin, Singapore Air Force—590 (MSEE)

CPT Brandon Chee, Singapore Army—590 (MSEE)

Major Goals

Over the course of FY23, our main objective was to understand how to model a 5G unmanned aerial network in order to test for security vulnerabilities. In particular, we needed to understand how to build a simulation architecture for a 5G enabled UAV network that uses the Robot Operating System version 2 (ROS 2).

In FY20 and FY21, through CRUSER funded research, we experimented with ROS 2, DDS and its security suites, as implemented on a specific Navy use case that was provided by PMW760. The use case involved a hybrid architecture consisting of WiFi and SATCOM links. We were successful in building a simulation model that integrated these different wireless communications links with DDS/ROS2 [1]. In FY23, we extended the work in [1] to integrate ROS 2 software with a 5G network wide area network that uses 5G New Radio (NR) links. ROS 2 designers have developed design specifications for ROS2-5G systems. Our envisioned system architecture is shown in Fig. 1 in which two UAVs running ROS applications communicate with the 5G control plane, while UAV data is relayed across the 5G data plane.

The network architecture that we have currently built in simulation (using Mininet) is shown in Fig. 2. This is an extension of the thesis in [1] in which we are now including 5G endpoints. The integration of ROS 2 and 5G was not a simple task and took much longer than anticipated due to compatibility issues. This implementation is now currently being troubleshooted and is nearly complete. Once finished, our plan is to 1) quantify the performance between a 5G at a UAV endpoint and its connecting tower (5G base station). We will examine a variety of mobility and

radio characteristics; and 2) study the 5G QoS identifiers and how it impacts the security of the UAV system in terms of identifying malicious control commands.

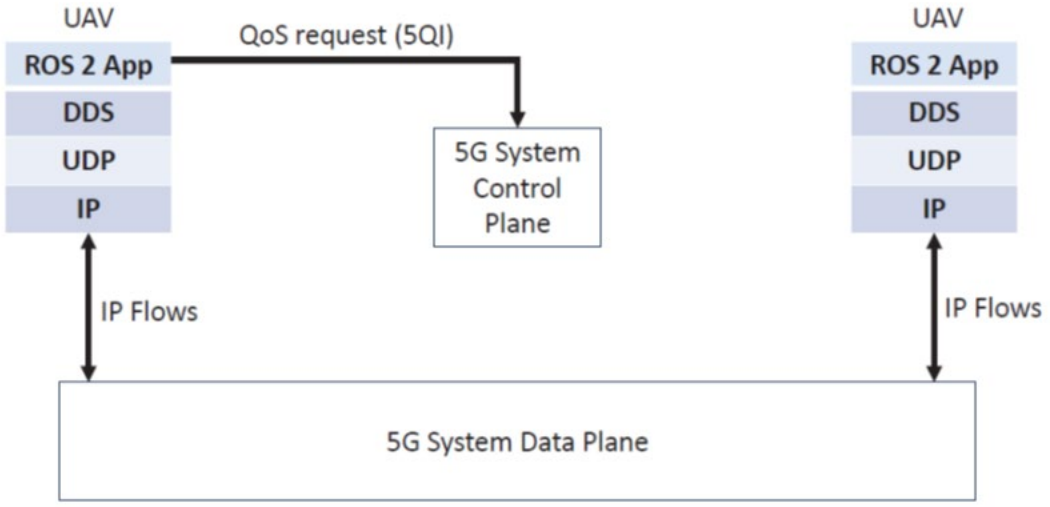

Figure 22: System architecture that includes two UAVs running the ROS2 application, communicating over the 5G control and data planes. Adapted from [2].

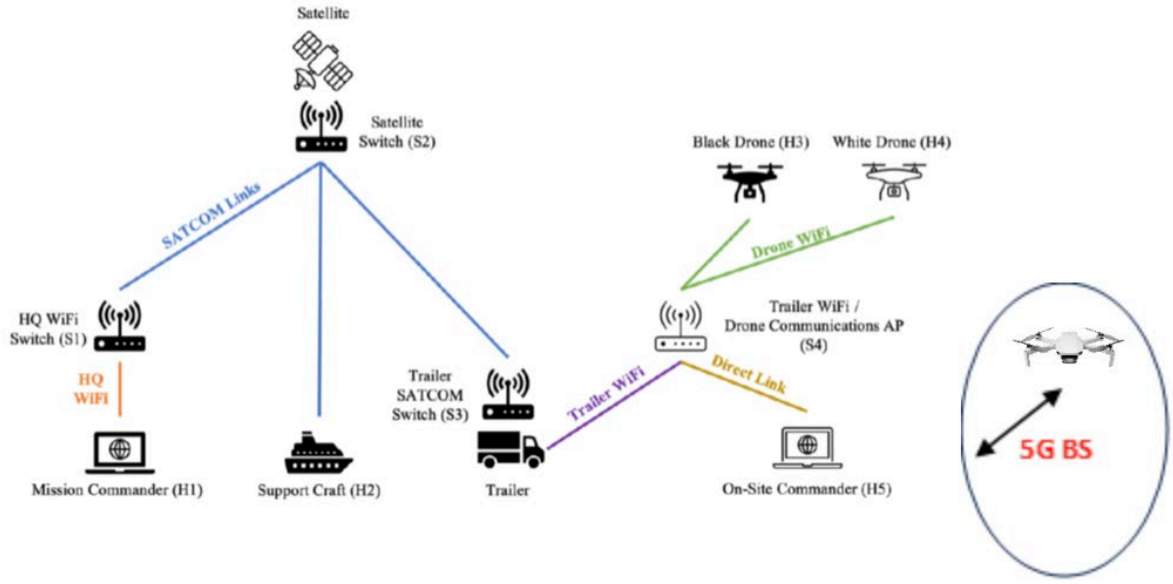

Figure 23: Mininet implementation of our proposed network architecture that includes one 5G endpoint, in which data from the drone will be offloaded to a central server using 5G communications links.

Accomplishments

- Integrated 5G/UAV network with multiple wireless links in simulation.

- Simulation sends traffic to and from 5G node to UAV.
- Current study of 5G QoS identifiers within a UAV system.
- Two NPS theses ongoing; expected graduation September 2024

Education

Thesis in progress: Maj. Kaijian Lin, Tentative Thesis Title, "Cyber Attack Execution on a Hybrid UAV Network Architecture," expected graduation September 2024.

Thesis in progress: CPT Brandon Chee, Tentative Thesis Title, "Performance Analysis of a 5G Integrated Hybrid UAV Network Topology," expected graduation September 2024.

Dissemination

As a result of thesis work, two conference publications are anticipated in Spring 2024.

Collaboration and Partnership

We are working with ONR Code 31 to assist in obtaining 5G specific data sets that can be used for security training. We are in preliminary conversations to obtain this data.

Transition

This work is being discussed for follow-up funding (FY25) at DASN-OE. The PI is currently the lead of a 3-year DASN-OE effort related to the security of shipboard power systems. The DASN-OE sponsor is interested in energy efficiency and security of unmanned systems. The foundational work sponsored by CRUSER will help us provide DASN-OE with a developed framework that will be used to request follow on funding to understand how this framework can be transitioned to an expeditionary environment.

References

[1] Yu Kheng Denny Cheng, "Performance Analysis of an Unmanned Systems Communications Network Using Data Distribution Service in a Lossy Environment," NPS MSEE Thesis, March 2021.

[2] ROS 2 and Unique Network Flows; https://design.ros2.org/articles/uniquenetworkflows.html

P. MANIPULATING CONTROL SURFACE ROUGHNESS ON UNCREWED UNDERWATER VEHICLES TO ACHIEVE SCALE-INDEPENDENT PERFORMANCE

Participants

Principal Investigator (PI):

Dr. Joseph Klamo <jklamo@nps.edu>

Associate Professor, Systems Engineering Dept, NPS

Co-PIs:

Dr. Alexander Laun <laun@usna.edu>

Assistant Professor, Naval Architecture & Ocean Engineering Dept, USNA

Dr. Justin Brown <jmbrown2@nps.edu>

Research Assistant Professor, Oceanography Dept, NPS

Students:

ENS Daniel Fohner

Curriculum 525, Undersea Warfare, NPS

Major Goals

The main goal of this effort was to establish a multi-year collaborative research project of interest to the U.S. Navy that involves the faculty and experimental facilities at the Naval Postgraduate School and the United States Naval Academy. The collaborative effort was established using this CRUSER SEED funding and the plan is to transition to Office of Naval Research funding to support the effort in subsequent years. The chosen research topic was to address the identified knowledge gap related to understanding how surface roughness affects the lift generation of control surfaces over a broad range of Reynolds numbers that spans robotic and manned underwater vehicles.

The approach for this effort was to use the CRUSER SEED funding to conduct a feasibility study to support the future experimental testing program and write a whitepaper proposal for future ONR funding. Control surfaces are characterized by multiple parameters such as aspect ratio, taper, and thickness, making the possible testing matrix parameter space large. The feasibility study explored the sensitivity of these parameters to control surface performance to identify the important parameters to include in the test matrix. The feasibility study was performed using

OpenFOAM and the simulation was first validated against previous experimental data collected at USNA. An identical setup to the USNA Eiffel wind tunnel was constructed with a variety of hydrofoil geometries and angles of attack. The simulation models turbulence using a Spalart–Allmaras DDES with 0.04-in resolution near the hydrofoil surface, 0.15-in resolution in the wake, and 0.6-in resolution at the boundaries. Figure 1 shows an example of the predicted wake behind a hydrofoil from the simulation which captures the characteristic turbulence and end-tip vortices.

Accomplishments:

- NPS personnel traveled to USNA to meet with faculty and learn about experimental testing capabilities at USNA that are not available at NPS.
  Created a simulation in OpenFOAM to predict control surface and validated output using experimental test results from USNA; the simulations showed good agreement in comparisons of the drag and lift coefficients of the control surfaces, with maximum deviations of about 15%.

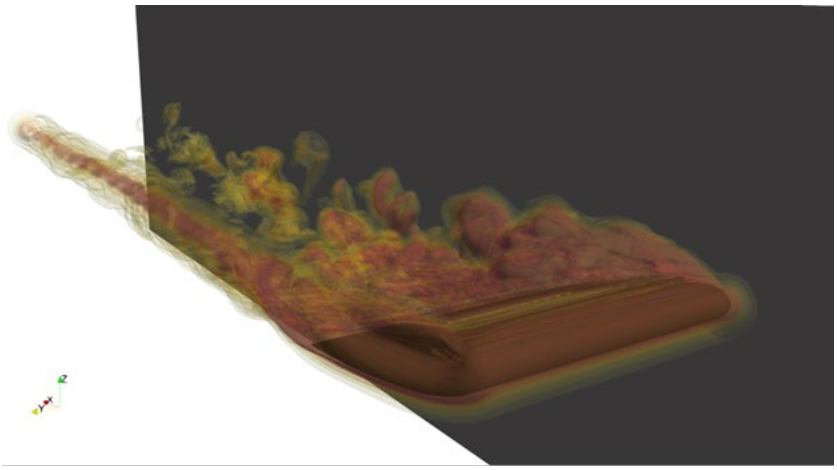

Figure 24: The flow past a NACA0018 hydrofoil with taper ratio of 0, aspect ratio of 2, and angle of attack of 15o.

- The sensitivity of control surface performance to the testing fixture design, such as attaching the control surface on a flat surface instead of a curved one, showed only weak effects on the performance coefficients (<5%).
- Produced a whitepaper proposal for ONR requesting multi-year funding for continuing established collaborative research effort between NPS and USNA to investigate speed and size dependency on control surface performance.

- Met with ONR Program Officer Dr. Peter Chang, Code 331, to discuss whitepaper and explore funding availability for FY25.

Education:

ENS Daniel Fohner, M.S thesis, "Using Computational Fluid Dynamics (CFD) to Optimize Hydrofoil Physical Parameters," Naval Postgraduate School, 2024 (expected).

Michael Grube, an ONR Science & Engineering Apprenticeship Program (SEAP) intern, supported the research effort during Summer 2023.

Dissemination:

No public dissemination

Collaboration and Partnership:

This research effort is an on-going collaborative effort between the Systems Engineering (PI Klamo) and Oceanography (Co-PI Brown) departments at the Naval Postgraduate School and the Naval Architecture & Ocean Engineering (Co-PI Laun) department at the United States Naval Academy. The collaboration is driven by the shared goal of educating U.S. Navy officers and the ability to share the unique experimental facilities at each institution to perform experimental testing.

Transition:

The deliverable from the CRUSER SEED funded portion of this effort was a whitepaper proposal that justifies and describes the future experimental tests. The proposal was presented to ONR Program Officer Dr. Peter Change from Code 331. We continue to have on-going discussions about establishing funding from ONR to begin in 2025. Concurrently, we have begun discussions with the SSN(X) program office about the possibility of having them share funding with ONR.

Klamo and Laun (2023) "Investigation of Speed-Dependent Control Surface Performance for Undersea Application." Whitepaper ONR proposal, Code 331 (FY2024/2025).

III. 2023 NAVAL INNOVATION EXCHANGE (NIX) INTELLIGENT AUTONOMOUS SYSTEMS (IAS) TEAM

Contributed by:

Sean Kragelund, IAS Team Lead, Research Asst. Prof., Mechanical & Aerospace Engineering
Kaitie Penry, Director or Research Innovation, Office of Research & Innovation
Cecilia Panella, Faculty Assoc. Research, Applied Design for Innovation, Defense Analysis
Kevin Jones, Research Assoc. Prof., Mechanical & Aerospace Eng.
LT Austin Dumas, USN, NPS Student: Space Systems Operations/Engineering (dual major)
LCDR Hans Lauzen, USN, NPS Student: Space Systems Operations
Capt Daniel Lim, USMC, NPS Student: Space Systems Ops./Systems Acq. Mgmt. (dual major)

Overview

In 2023, CRUSER initiated a Naval Innovation Exchange (NIX) team focused on Intelligent Autonomous Systems (IAS). Working in tandem with the NPS Department of Defense Management's Interdisciplinary Transition Team (ITT), the NIX program's mission is to create, connect, and support student-faculty-industry teams to accelerate the adoption of innovative solutions to Naval problems, from idea curation to prototype development, field-testing, and identifying an acquisition strategy for transitioning solutions to Fleet stakeholders. With CRUSER support, the NIX IAS team conducted the following activities in 2023:

Outreach

The NIX IAS Team provided a briefing to the Pentagon's Unmanned Task Force (UTF) to describe the NPS NIX concept and invite Fleet stakeholders to the NIX IAS Concept Exploration workshop held on the NPS campus on 8-9 JUN. This workshop had 60 active participants from across the Naval research and development enterprise, including faculty and students from NPS, researchers and engineers from Warfare Centers and University Affiliated Research Centers, and warfighters from various Fleet commands. The workshop featured plenary talks by Dr. Jason Stack (SES), Director of ONR's Ocean, Atmosphere, & Space Research Division and Deputy Director of the UTF; and Mr. Noam Oz, Director of Innovation Operations for NavalX and Sprint & Transition Lead for the UTF; as well as a panel by NPS subject matter

experts in autonomous systems, field experimentation, and defense acquisition. Small teams explored aspects of the problem "How might we identify and prioritize intelligent autonomous systems (IAS) research and development opportunities of the most interest to Naval leadership and align work with affiliated warfare center projects and industry partners?" One team's recommendations led to an article published in Defense Acquisition Magazine[1] by LCDR Matthew Litton, USN (NPS student); Michael Richardson (NPS researcher and director of the Joint Interagency Field Experimentation (JIFX) program; and Ari Goodman (Artificial Intelligence Science and Technology lead at Naval Air Warfare Center Aircraft Division-Lakehurst. This workshop was also featured in an NPS News article about the NIX program[2]. In addition, Dr. Kragelund and Ms. Penry served on the 2023 Warfare Innovation Continuum's Discovery Panel focused on the NPS NIX.

CRUSER support enabled several other NIX IAS engagements with external stakeholders. Dr. Kragelund gave a talk entitled "Partnering with the Naval Innovation Exchange (NIX) at NPS" during the NAVAIR Autonomy & AI Community of Interest meeting in August 2023. That same month, he also traveled to NIWC-Pacific and met with Spencer Koroly, Project Manager, Unmanned Systems S&T, to discuss collaborating with the NPS NIX teams for IAS and additive manufacturing.

Ms. Penry traveled to Washington, DC in August, where she met with Defense Innovation Unit to initiate work on a Memo of Understanding with NPS. She discussed NIX initiatives with several folks at ONR, including Dr. Jason Stack; LtCol Jack Long, Artificial Intelligence Lead; Billy Short, Expeditionary Portfolio; as well as Naval X, USD R&E, and RDER about funding and field experimentation opportunities. Ms. Penry also attended the Future Naval Requirements Roundtable at ONR in November, where she gave a presentation on NIX IAS Team projects and met with the Office of Strategic Capital, Steve Brock (Senior SECNAV advisor), and SES Rick Quade, OPNAV N94. With CRUSER support, Ms. Penry also stood up the NPS Innovation Pillar Committee and its subcommittees and developed infrastructure to support NIX processes.

[1] M. Litton, M. Richardson, and A. Goodman, "Battlefield autonomy: a proven way forward," Defense Acquisition Magazine, vol. 52, no. 6, pp. 8-12, Nov-Dec. 2023. Available: https://www.dau.edu/library/defense-atl/DefAcqMag-Nov-dec23

[2] https://nps.edu/-/empowering-student-ideas-nps-introduces-the-naval-innovation-exchange

NIX IAS Projects

Satellite Communications and Autonomous Vehicles for Naval Special Warfare

A NIX IAS team comprised of Space Systems Operations students U.S. Navy LT Austin Dumas (dual majoring in Space Systems Engineering), LCDR Hans Lauzen, and U.S. Marine Corps Capt. Daniel Lim (dual majoring in Systems Acquisition Management) are researching how Naval Special Warfare (NSW) can combine proliferated Low-Earth Orbit (pLEO) architectures and small autonomous surface vessels (ASVs) to enable Over-the-Horizon Targeting (OTH-T) and close the Joint Force kill chain. Leveraging an NPS Cooperative Research and Development Agreement (CRADA) with Saronic Technologies, this student-led team has successfully demonstrated operations with prototype, low-observable ASVs utilizing resilient space-based architecture (Starlink/Iridium/SATPAQ) for beyond line-of-sight (BLOS) command and control (C2) and targeting. NAVSPECWARCOM, along with NSWG-4 and NSWG-8, is sponsoring these students' thesis research, and CRUSER has provided funding for students and their faculty advisors to attend planning conferences, in-water experiments, and Navy exercises.

LT Dumas, LCDR Lauzen, and Capt. Lim, working with DDM's ITT to develop an acquisition strategy for the team's proposed technology solution, have diligently coordinated with stakeholders including PEO SDA(SOCOM), PEO Maritime (SOCOM), PEO USC(USN), PEO C4I(USN), PACFLT, INDOPACOM, DIU, and NavalX. In addition, LT Dumas developed a test plan for NSWG-4 to evaluate prototype ASVs at Large Scale Exercise Gray Flag '23 (San Diego) in August. Preliminary test results included successful launch & recovery from multiple NSW combatant craft (a first) and BLOS control and data relay through Starlink and Iridium pLEO constellations. Upon the completion of testing, Ms. Panella facilitated a mini-workshop for NSWG-4, SBT-12, WARCOM N8, Saronic Engineers, NPS faculty and students to brainstorm additional NIX IAS projects and incorporate feedback into the student teams' evolving CONEMP development. LT Dumas and LT Forrest Hansen, an NPS student dual majoring in Applied Design for Innovation and Space Systems Operations presented their preliminary findings at the Naval Warfare Studies Institute (NWSI) Seapower Conversation event in December. Additionally, Dumas, Lauzen and Lim were able to provide an in-depth brief on the results of their work to senior representatives from resource sponsors and stakeholders.

Among those briefed on the students' work were Vice Adm. Francis Morley, Principal Military Deputy, ASN RD&A, and Rear Adm. Kurt Rothenhaus, Chief of Naval Research.

Additional testing occurred during October's JIFX 24-1, at both Camp Roberts, CA and Lake Bastrop, TX. Representatives from the SOCOM PEO SDA's program manager for Unmanned systems Autonomy and Interoperability (USAI) joined the NIX IAS team to observe Saronic's ASV sea trials in Texas, while government stakeholders such as SOCOM, WARCOM, CENTCOM, and OSD were able to view live sensor feeds and remotely operate the ASV from Camp Roberts. This remote experiment utilized multiple communication pathways including Starlink, 5G, LTE, Sylvus mobile ad-hoc network, and Iridium. Additional testing investigated another viable C2 pathway using the Higher Ground SATPAQ Trackpod. This successful test event increased collaboration between NPS, Saronic, and Higher Ground, and SOCOM's USAI Program, leading to a new a CRUSER seed project for FY24. Finally, CRUSER funding has allowed LT Dumas to attend planning meetings for this project to participate in the PACFLT UxS Integrated Battle Problem (IBP) 24.1 in March 2024.

Aqua-Quad Innovations

In September 2023, a new NIX IAS project was formed around the Aqua-Quad, a novel unmanned aerial system (UAS) conceived, designed, and produced at NPS. Invented by Dr. Kevin Jones and Dr. Vladimir Dobrokhodov with CRUSER seed funding, the Aqua-Quad UAS is capable of landing and taking off from the sea surface, making it useful for a number of maritime sensing. This project was selected for further development due to its high technology readiness level (TRL) and ongoing relationship with the Naval Undersea Warfare Center—Keyport. After Drs. Jones and Kragelund presented this project to DDM's Ray Jones, Jeff Dunlap, and Robert Mortlock, the Aqua-Quad was selected for study by the ITT, where DDM students can develop a transition/acquisition strategy for this technology.

Working with Dr. Jones, three MAE students (ENS Nafus, ENS Trauger, and ENS Flaherty) are researching ways to enhance the Aqua-Quad to increase speed and endurance through more efficient cruise flight. Specifically, this team has developed a modified MosquitoHawk quadcopter to carry a 5th motor for lateral thrust. Initial flight tests while manually controlling the 5th motor during cruise flight have demonstrated the ability to fly with zero pitch angle, while significantly reducing the power required from the lift motors. The team

has also been fabricating mock solar arrays for the Aqua-Quad to provide experimental lift and drag data from flight tests, which will support several ongoing student theses. Finally, ENS Nafus has been developing a prototype with two lateral thrusters nested between the fore and aft lift propellers, increasing their efficiency.

IV. COMMUNITY OF INTEREST

A. MEMBERSHIP

The CRUSER community of interest (COI) membership went down slightly to ~2,687 members (Dec 2023) when we did some duplicate removal and list cleanup. The membership breakdown is 34% general population, 27% education, 18% military, and 2% government.

B. MONTHLY MEETING PROGRAM

CRUSER holds a monthly community meeting generally on the first Monday of the month at the noon hour (Pacific time). In 2023, 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 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 2023, there were 12 monthly CRUSER meetings featuring 24 presentations.

Table 4: 2023 CRUSER Monthly Meetings

Month	Presentation Title(s)	Presenter(s)
January	Dr. Mara Orescanin, Dept of Oceanography, NPS - CRUSER SEED Research Program	Application Results
	Dr. Eric Frew, Professor, Ann and H.J. Smead Aerospace Engineering Sciences Department, University of Colorado Boulder	Innovation Beyond Integration: The Center for Autonomous Air Mobility and Sensing
February	Dr. Troy Ansell, MAE Dept, NPS	Printing and Poling Piezoelectric Polymer Composites with Boron Nitride Nanotubes
	LT Jiles Maness, LTJG Chris Mears, Defense Analysis Students and LT Dumas, Space Systems Student, NPS	Hyper-Enabling Operators with Unmanned Systems and pLEO Constellations

March	Jessica Herman, Professor of Practice, NPS Dennis Danko, CDR USN (Ret), JPEM Program Manage	Robotics Certificate Update Joint Prototyping and Experimentation Maritime
April	LT Marissa Samons, SURFDEVRON ONE, USN and LT Jorge Rivas, USVDIV1, USN Dr. Abe Clark, Dept. of Physics and Dr. Isaac Kaminer, Dept. of Mechanical Engineering, NPS	Medium and Large USV 101 Scaling and Trade-offs in Adversarial Swarm Engagements
May	Dr. Christopher Brophy, Dept. of Mechanical and Aerospace Engineering, NPS Dr. Don Brutzman, Dept. of Information Sciences, NPS	Progress Towards a Rapid-Response Counter-Swarm Delivery System Ocean Power Technology (OPT) PB3 PowerBuoy Opportunities for NPS Applied Research
June	LT Devon Florendo, Systems Engineering Student, NPS Kristen Fletcher & Marina Lesse, Energy Academic Group, NPS	Using Design-Test-Build cycles to Demonstrate Propulsion in a Karman Vortex Using a Flexible Body UxS: Governance and Policy Research at NPS
July	Capt. Deondra Irby, Information Warfare Systems Engineering Student, NPS Doug Horner, Chair, Undersea Warfare Academic Group, NPS and Geoff Xie, Computer Science Dept, NPS	Woman's Impact Tech Conference Behavior Integrated Optimization for Networked Control Systems (BION)
August	LtCol Scott Humr, PhD Candidate, Information Sciences, NPS Dr. Shelley Gallup, Information Sciences, NPS	Judgment and Temporal Evolution of Trust in Artificial Intelligence-Supported Decision-Making LMACC: Lightly Manned Autonomous Combat Capability

September	Dr. Ruriko Yoshida, Dept. of Operations Research, NPS Dr. Britta Hale, Dept. of Computer Science, NPS	Randomized Routing Strategies for Deception in Mobile Networked Control Systems Changing the Paradigm for UxS Security, Robustness, and Efficiency in Communication Connections
October	John Joseph, Oceanography Department, NPS Dr. Vlad Dobrokhodov, MAE Department, NPS	PSAP: Soundscape Listening Forevermore Navigating Complex Winds: Fuel-Optimal Guidance for Ultra-Long Endurance Flight
November	Kenny Watts, Implevation, LLC Dr. Preetha Thulasiraman, ECE Department, NPS	Overview of Army Redstone Arsenal Unmanned Aircraft Systems RDT&E Entities and Programs 5G and Networked UAV Systems: Opportunities and Constraints
December	Dr. Emre Gunduz, MAE Dept, NPS CAPT Matthew LaPointe, Senior Advisor, OPNAV N13 for Artificial Intelligence and Intelligent Robotic Autonomous Systems	Additive Manufacturing Building Update Robotics Warfare Specialist, Navy Robotics and Autonomy on the Tactical Edge

V. RESEARCH INFRASTRUCTURE

A. JOINT INTERAGENCY FIELD EXPERIMENTATION

Overview

The JIFX team leads experimentation in alternative methods to enable rapid technological development by cultivating a community of interest and hosting broadly scoped quarterly collaborative field events which enable DoD, US government, and allied stakeholders to identify, influence, and accelerate early-stage technology development that address national and collective security challenges. JIFX is primarily supported by OUSD/R&E but several CRUSER Seed Research projects leverage this group for experimentation. CRUSER also augments the JIFX budget to enable experimentation opportunities for CRUSER members.

In 2023, JIFX hosted four quarterly events at the NPS Field Laboratory at Camp Roberts Army National Guard Base.

Primary Contacts

- Mike Richardson, JIFX Director, mrichard@nps.edu
- Ashley Book, JIFX Event Manager, Ashley.book@nps.edu

JIFX 2023 Events

- 6-10 February – Focus Area: Human Performance Monitoring & Situational Awareness
- 1-5 May – Focus Area: Autonomous Logistics Enabled by Artificial Intelligence and Machine Learning
- 7-11 August – Focus Area: Autonomy & Human Machine Teaming
- 23-27 October – Focus Area: Operations at the Edge

Accomplishments

- Total Experiments: 88
- Total Participants: 724

Dissemination:

JIFX 23-2 Quicklook

JIFX 23-3 Quicklook

JIFX 23-4 Quicklook

JIFX 24-1 Quicklook

Future Planning

JIFX will continue into 2024 with the following events:

- JIFX 24-2: 5 - 9 February 2024
- JIFX 24-3: 13 - 17 May 2024
- JIFX 24-2: 5 - 9 August 2024
- JIFX 25-1: Fall 2024

B. ROBODOJO

Participants

Principal Investigator (PI):

Kristen Tsolis ktsolis@nps.edu

Additional Contacts:

PO2 Rosado-Rosario, enlisted support staff

Students:

We serve all curricula at the Naval Postgraduate School.

Major Goals

The RoboDojo is a dynamic innovation space (located on NPS campus in Root Hall, Room 125) where students, staff, and faculty 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, Right to Repair, and Drone Racing. The RoboDojo represents a grassroots initiative to promote collaborative and community learning.

Accomplishments:

- Offered 65 workshops led by students, faculty, and staff members. Many of these workshops led to direct support of student thesis or class projects.
- Our biggest accomplishment has simply been supporting collaborative, engaged learning and meaningful synergies across curricula. Students working in the lab have gone on to

start up a Makers Club and to reinvigorate the Radio Club, and they will soon be starting up a Drone Racing club.

- With CRUSER support, the lab has refreshed major equipment including our laser cutter/engraver, our FDM 3D printers, and our Formlabs resin printers. This critical equipment expenditure has helped us maintain quality of service to the campus community and to alleviate lab repair requests for our limited lab support.
- Visited and brought back some best practices from makerspaces at the Naval Academy, MIT, RISD, and Autodesk.

Figure 25: NPS Students participate in a RoboDojo workshop.

Education:

- Classes supported by this effort: ME2801, Intro to Control Systems; DA3304, Rapid Prototyping for the Warfighter; ME4901, Advanced Topics in Mechanical (Aerospace) Engineering

- Directly supported more than 50 thesis projects and dissertations in Mechanical Engineering, Systems Engineering, Computer Science, Physics, Defense Analysis, Space Systems, and other departments.

Dissemination:

- The students have published their thesis, dissertations, and articles, and we have been part of the support network with our work in the RoboDojo.
- Article regarding support for Coast Guard operations will be forthcoming in 2024.

Collaboration and Partnership:

- 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.
- USCG Monterey Station: Rapid Prototyping experimentation with this unit.

Transition:

We have spoken with NPS leadership about NPS providing partial future funding of the RoboDojo. Campus leadership is planning to move the RoboDojo to a much larger space in Halligan Hall within the next five years, and this expanded space will allow a wider array of capabilities for lab users.

VI. EDUCATION

A. STUDENT TRAVEL

Point of Contact

Jean Ferreira, CRUSER Operations Manager

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.

Accomplishments

During 2023, student members executed 30 travel events, for a total cost of $57,761, related to CRUSER research projects. Destinations included, but were not limited to the following:

- Student presentation and participation in the American Geophysical Union conference in San Francisco, CA.
- JIFX participation and UAV swarm flight testing; February, May, August, and November; Camp Roberts, CA.
- Student participation on panel discussion titled “Innovations Across Domains and Sectors” in London.
- Collaboration with Naval Special Warfare Group 4, in San Diego, CA testing and experimentation support of IAS research
- Student participation in testing of the Mokai Kayak platform at the ONR field exercise, Sullivan IN, Texas, and Monterey County CA.
- Student participation in the FPC for the PACFLEET Integrated Battle Problem 24.1

B. ROBOTICS ENGINEERING GRADUATE CERTIFICATE

Overview

Since enrolling the first students in July 2020, the Robotics Engineering Certificate has provided students across the NR&DE workforce with technical, relevant education opportunities in the field of Autonomous Systems. After running two cohorts per year to accommodate the high level of initial interest, in the summer of 2022 the program transitioned to a steady-state target of one entry per year. Interest in the program remains strong, including among active-duty military applicants, with strong civilian participation from over a dozen diverse commands. Courses are offered in a fully remote format, with flexibility to allow for asynchronous participation. The Robotics Engineering Graduate Certificate is funded through NR&DE Commands and CRUSER funds support course development, student travel, etc.

Point of Contact:
Jessica Herman, Curriculum 223 Academic Associate

Accomplishments:
In June of 2023, the Robotics Engineering Certificate graduated our fifth cohort, 22-4. Over the past 3 years, 60 students have successfully met all requirements to earn the Certificate.

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

Fundamental GNC Algorithms of Autonomous Robotics

- ME4800 Machine Learning for Autonomous Operations

Alternate elective/ applications courses may be offered based on the needs of sponsoring organizations or department course scheduling constraints.

Future:

In July of 2023, 9 students in Cohort 23-4 began their first course of the Certificate program. They are joined in the first two classes by 10 newly-commissioned Ensigns, stationed at NAS Pensacola, who are enrolled in a graduate education pilot program while awaiting their start dates for API and flight school.

The program is accepting applications for admission through the end of March for our next planned cohort, beginning in the 4th quarter of academic year 2024 (Cohort 24-4).

VII. CONCEPT GENERATION

A. WARFARE INNOVATION CONTINUUM

The Naval Postgraduate School's annual Warfare Innovation Continuum (WIC) Workshop acts as an innovation engine, leveraging operationally-focused students and defense-oriented faculty at the Naval Postgraduate School (NPS) to address complex fleet issues – from technical to ethical issues and from concept-generation to experimentation. Small teams of early career professionals from the fleet, Navy labs, industry, and academia with diverse experience levels and perspectives spend three and a half days rapidly generating concepts of employment and evaluate risk within a future conflict scenario. Government, military, industry, and academic leaders vet these ideas before disseminating results back to Naval leadership.

WIC Workshops are coordinated by the NWSI Concepts Branch, which is responsible for warfighting concept generation and development activities across the named NWSI Research Group and Task Force topic areas, and across the NPS campus. This workshop was co-sponsored by CRUSER and supported by OR&I.

This rapid concept generation workshop was held 18-21 September 2023 and included 108 active participants, with just over 80 on the NPS campus in Monterey and the rest on the NPS "Virtual Campus" via ZoomGov.

2023 Design Challenge

How might the confluence of new technologies provide opportunities for new operational concepts in executing integrated naval campaigning across the full spectrum of conflict?
WIC 2023 Scenario: World War in the 21st Century

Event Description

Concept generation teams composed of NPS students and faculty, government scientists, and industry partners with diverse perspectives addressed amphibious, gray zone, and coalition operations; contested logistics; and future vertical take-off and landing capabilities.

- Three U.S. only teams working on the NPS campus in Monterey in classified spaces on advanced mining, undersea operations, and long-range fires.
- Four Discovery Panels included speakers from the operating forces, NPS, Naval warfare centers, and industry, many of them recognized leaders in their fields.

Equal in significance to the concept outcomes was the opportunity to build and grow a diverse and rich network of NPS students and faculty, fleet and fleet marine force warfighters, warfare center engineers, and industry partners.

Participants

This workshop engaged 108 active participants from NPS, industry, academia, Naval warfare centers, warfighting development centers, the Fleet, and systems commands in addition to 73 registered as observers. International participants from Australia, Taiwan, Brazil, Indonesia, Turkey, South Korea, Singapore, India, and Columbia ensured a global perspective.

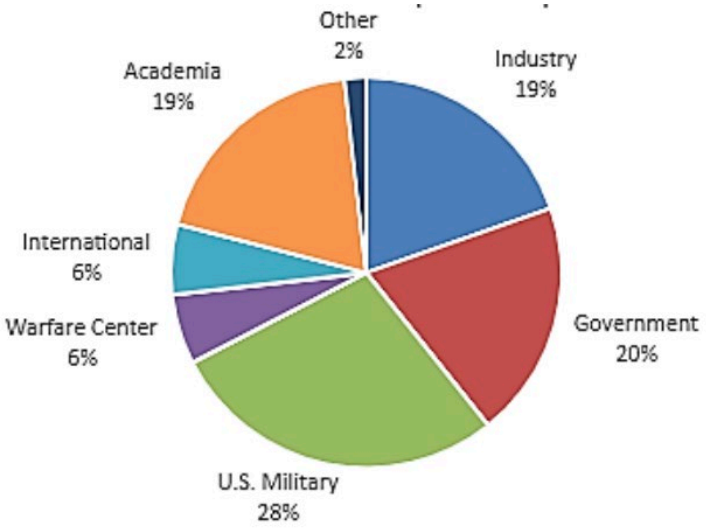

Figure 26: WIC Workshop Participants

Eight Concept Generation Teams were facilitated through a three and a half-day rapid concept generation process and produced the following concepts in nine and a half hours:

Table 5: 2023 WIC Concept Generation Teams and Concepts

Team	Concept	Description
Amphib Ops	HiDRA & UxVs	1) Highly distributable rapid assault (HiDRA) family of ship-to-shore connectors supporting

		transport and landing force defense; and 2) a network of autonomous surface, subsurface, and aerial vehicles (UxVs) to support amphibious operations in the year 2040
Coalition Ops	ACTORS	Coalition Ops ACTOR Advanced coalition training operations readiness (ACTOR)
Gray Zone Ops	Coordinated Influence	A coordinated and enduring influence campaign encompassing whole of government engagements with partners and allies
Contested Logistics	Data Advantage	Joint logistics data standards enable evolution of logistics necessary to fight a future integrated naval campaign across the spectrum of conflict
Future VTOL	Future VTOL+	A defined set of future VTOL missions and challenges, and human machine teaming concepts and capabilities
Advanced Mining	RADE, BRAIN, UncLE REMUS & CERBERUS	1) Rapid air-deployed effector (RADE); 2) buoy remote arming and intel network (BRAIN); 3) Uncrewed landing effector REMUS (UncLE REMUS); and 4) clandestine extended range balloon, effectors, and reconnaissance undersea submersible (CERBERUS)
Undersea Ops	MOCCFAP & DLCO	1) Modification and repurpose of civilian craft to help shape the surface and undersea theater; and 2) concept to deter, lure, and create opportunity
Long Range Fires	Concept Auditing	Evaluation of five external stakeholder concepts for operational and programmatic feasibility and risk

Key Takeaways:

1. Coalitions – integrated, not just coordinated, coalition operations are essential for future success. Relationships with allies and partners must be developed today to operate successfully together in the future.
2. Data is Key – data standardization is critical to realize the full potential of AI/ML supported future capabilities
3. Human-Machine Teams – clever human-machine teaming will be key to future operations.

Future:

The concepts generated during this WIC Workshop will feed into the Naval Innovation Exchange (NIX) teams, Innovation Capstone Projects (ICP), and the Naval Innovation Center (NIC) at NPS. ¬ Naval Innovation Exchange (NIX) is multidisciplinary teams of NPS students and faculty focused on developing prototype research solutions ¬ Innovation Capstone Projects (ICP) led by NPS students will develop acquisition strategies and transition plans for Program Executive Offices to adopt. ¬ Naval Innovation Center (NIC) at NPS is the Secretary of the Navy's initiative to leverage the power of American innovation for national security. All efforts will inform future force design efforts. Contact wiw@nps.edu for the full final report for the 2023 WIC.

VIII. STEM ACTIVITIES

With support from the ONR Naval STEM Coordination Office CRUSER championed additional "Design Challenges" geared at high school students and through the online platform, Scoutlier. These specific challenges in 2023 were focused on automation surrounding climate change, and challenged high school teams to design an app that could make a local impact on climate. The winning team fully automated tracking soil nutrients to detect health trends resulting from changes to precipitation. Representative Jimmy Panetta attended the awards ceremony in May 2023, where the four winning teams were honored with prizes supported by the NPS Foundation.

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. This fall, CRUSER has sponsored an additional two challenges: One to design a smart ocean mooring that will return to the user to gather meteorological/oceanographic data during extreme events and the second to design an autonomous monitoring system for water quality of local watersheds, with a focus on interactions between watersheds and the coastal ocean.

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