NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

CONSORTIUM FOR ROBOTICS AND UNMANNED SYSTEMS EDUCATION AND RESEARCH (CRUSER) FY16 ANNUAL REPORT

Prepared by

Lyla Englehorn, Faculty Associate – Research

December 2016

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Prepared for: Raymond R. Buettner Jr., CRUSER Director

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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 FY16 annual report summarizes CRUSER activities in its sixth year of operations (2016), and highlights future plans.

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NAVAL POSTGRADUATE SCHOOL
Monterey, California 93943-5000

Ronald A. Route
President

Steven R. Lerman
Provost

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This report was prepared by:

____
Lyla Englehorn, MPP
CRUSER Associate Director

Reviewed by:

____
Raymond R. Buettner Jr., PhD
CRUSER Director

Released by:

____
Jeffrey D. Paduan, PhD
Dean of Research

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

FY16 Annual Report

Prepared by Lyla Englehorn, CRUSER Director of Concept Generation
for Dr. Raymond R. Buettner Jr., CRUSER Director; Dr. Brian Bingham, CRUSER Deputy Director
and Dr. Timothy H. Chung, CRUSER Deputy Director through April 2016

NAVAL POSTGRADUATE SCHOOL

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Since 2011 the Naval Postgraduate School (NPS) Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) has sought to create and nourish 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). Originally authorized by an Under Secretary of the Navy (USECNAV) memorandum dated 1 February 2011, CRUSER is an initiative designed to build an inclusive community of interest around the application of unmanned systems in naval operations. CRUSER seeks to catalyze these efforts, both internal and external to NPS, by facilitating active means of collaboration, providing a mechanism for information exchange among researchers and educators with collaborative interests, fostering innovation through directed programs of operational experimentation, and supporting the development of an array of educational ventures. These activities are consider to be in direct support of the Secretary of the Navy's (SECNAV) priorities regarding unmanned systems

CRUSER captures a broad array of issues related to emerging robotic and autonomy related technologies, and encompassing the successful research, education, and experimentation efforts in unmanned systems currently ongoing at NPS and across the naval enterprise. Controls, sensors, design, architectures, human capital resource requirements, concept generation, risk analysis, cybersecurity, and field experimentation are just a few interest points. In February 2013 the CRUSER community of interest reached the 1,000-member mark, and continued to grow. As a demonstration of CRUSER's relevance and reputation, as of September 2016 the CRUSER community of interest included nearly 3,200 members from government, academia and industry.

In FY16 CRUSER's primary focus remained impacting the larger naval and defense communities. Support to individual professors provided direct impact on teaching in the NPS classroom. CRUSER supported classroom projects designed provide input for larger naval wargames as well as providing direct feedback to operators and engineers in the fleet and at warfare centers. This FY16 Annual Report provides a summary of activities during CRUSER's sixth year of operation and highlights future plans.

I. BACKGROUND

From Technical to Ethical
From Concept Generation to Experimentation

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

CRUSER encompasses the successful research, education, and experimentation efforts in unmanned systems currently ongoing at NPS and across the naval enterprise. Controls, sensors, design, architectures, human capital resource requirements, concept generation, risk analysis, cybersecurity, and field experimentation are just a few interest points.

Major aligned events starting in FY11 through FY16 are plotted along major program innovation threads (*see Figure 1*) starting with concept generation workshops, developed in technical symposia, and demonstrated in field experimentation to test selected technologies. These activities each have separate reports, and are available upon request. However, research and education will continue to include a broader landscape than just mission areas.

Figure 1. CRUSER program innovation threads as of September 2016

A. VISION

At the direction of the SECNAV, NPS leverages its long-standing experience and expertise in the research and education of robotics and unmanned systems to support the Navy's 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 discipline boundaries.

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 robotics and unmanned systems into existing joint and naval field experiments, exercises, and war games; as well as host specific events, both experimental and educational. The Consortium currently hosts classified and unclassified websites and has established networking and collaborative environments for the community of interest.

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 will be an important benefit of CRUSER, making the Consortium a unique and indispensable resource for the Navy while highlighting the educational mission of NPS.

Specific CRUSER goals continue to be:

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

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

B. MANAGEMENT

CRUSER is organized as a regular NPS research project except with a more extensive charter than most reimbursable projects. It has both an oversight organization and coordination team. The Director, with the support of a lean research and administrative staff, leads CRUSER and executes the collaborative vision for the Consortium. The Director encourages, engages, and enhances on-campus efforts among all four graduate schools and existing centers and institutes. Faculty and students from all curricula with an interest in the development of unmanned systems are encouraged to contribute and participate.

CRUSER continues to build upon existing infrastructure involving research in robotics and unmanned systems, including the Joint Interagency Field Experimentation (JIFX) program, the Center for Autonomous Vehicle Research (CAVR), the Advanced Robotics Systems Engineering Lab (ARSENL), and the Center for Network Innovation and Experimentation (CENETIX). These and other programs continue to be major partners in CRUSER research endeavors. The strong interdisciplinary approach of the Consortium is supported by active interest in the Operations Research, Mechanical and Aerospace Engineering, Information and Computer Sciences, Systems Engineering, Electrical and Computer Engineering, Space Systems, Physics, Applied Mathematics, Oceanography, Meteorology, Defense Analysis, and Business Administration Departments at the Naval Postgraduate School. Externally, CRUSER leverages NPS's substantial experience in building collaborative communities to create a dynamic learning environment that engages fleet operators, government experts, industry leaders and academic researchers around the naval unmanned systems challenges. Additionally, CRUSER leverages USECNAV and ONR relationships with external organizations to include the Deputy Assistant Secretary of the Navy (DASN) for Unmanned Systems, the Office of Naval Research (ONR), the U.S. Naval Research Laboratory (NRL), various Office of the Chief of Naval Operations (OPNAV) entities, Naval Air Systems Command (NAVAIR), Naval Sea Systems Command (NAVSEA), Marine Corps Warfighting Laboratory (MCWL), Naval Air Warfare Center (NAWC) Weapons Division, Naval Undersea Warfare Center (NUWC) Keyport, and Space and Naval Warfare Systems Command (SSC) Pacific among others.

A variety of NPS courses and educational resources contribute to an integrated academic program. CRUSER augments this holistic academic approach by providing diverse topics and aligned projects for courses not traditionally associated with unmanned systems focus areas such as: cost estimation of future systems; data mining large sensor data sets; and manpower and personnel implications of unmanned systems.

The Director guides the activities of CRUSER such that they are continually aligned with the unmanned systems priorities of the Navy and Marine Corps. The Director reports to the NPS Dean of Research, and continues to serve as a conduit between associated faculty and students at the Naval Postgraduate School and partnering institutions and agencies.

The Director is supported by an NPS Advisory Committee comprising the NPS Dean of Research, the Undersea Warfare Chair, the Expeditionary and Mine Warfare Chair, the Assistant Chief of Staff for Aviation Activities, the Senior Information Warfare Officer, the Surface

Warfare Chair, and senior representatives of the other branches of the armed services (USMC, USA, and USAF). This committee ensures that the fleet and its operations remain a primary consideration in CRUSER activities to include the selection of activities funded by CRUSER.

C. FY16 PROGRAM ACTIVITY SUMMARY

The CRUSER FY15 Annual Report concluded with a list of proposed FY16 activities. Now that FY16 is at a close CRUSER has concluded the first four innovation threads, are developing the fifth, and have just begun a sixth thread as planned. Additional progress on planned activities in FY16 included:

- CRUSER continued to fund the integration of robotics and unmanned systems issues into appropriate courses and support development of educational materials that will enable the Navy and Marine Corps officers afloat to become familiar with the challenges associated with the development and operational employment of these systems.

- CRUSER initiated the Robotics Education (Robo-Edu) Design Challenge was launched in March 2016 to explore UxS training and education across the greater Naval Enterprise meeting the obligation to prepare the next generation of warfighters to employ robotics and autonomous systems in the battlespace.

- CRUSER hosted the annual NPS CRUSER Technical Continuum (TechCon) in July 2016 to demonstrate technologies to explore development of the concepts generated the fall concept generation workshops.

- CRUSER sponsored experimentation of the most promising technologies presented CRUSER TechCon 2015.

- CRUSER continued to support summer internships from the service academy students to work in labs across NPS throughout FY16.

- CRUSER funded NPS student trips in FY16 to participate in research and experimentation dealing with all aspects of unmanned systems.

- CRUSER closed FY16 with a concept generation workshop during NPS Thesis & Research Week, 19-22 September 2016.

- CRUSER continued Community of Interest database generation, newsletter production and distribution, and monthly community-wide meetings.

CRUSER supported a variety of Naval and OSD Policy development activities to include the Under Secretary of the Navy’s Unmanned Systems TTX, the Navy’s Unmanned Systems Roadmap, ALNAV development, and the OSD Unmanned Systems Roadmap.

CRUSER also initiated work on an autonomy study for the DUSN-M, provided formal presentations to the National Academies, and served as mentors for the OSD sponsored Hacking for Defense program.

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II. PRIORITIES

Concept generation, education, research, experimentation, and outreach are all basic tenets for CRUSER. To support the four CRUSER goals, various activities and research initiatives will occur, ranging from unmanned systems innovation symposia and technical symposia to experimentation and research projects. To support the four CRUSER goals, various activities and research initiatives will occur, ranging from unmanned systems innovation symposia and technical symposia to experimentation and research projects. CRUSER executed just over $4M in the FY16 cycle, and anticipates funding at the same level for FY17. Activities for each year are briefed to the Advisory Board and require approval from the sponsor.

FY16 saw the CRUSER leadership team transition as the original Deputy Director, Dr. Timothy Chung moved on to a position with DARPA and CRUSER Operations Manager Lisa Trawick also took a position outside of NPS. CRUSER welcomed Dr. Brian Bingham as the Deputy Director, and Ms. Jean Ferreira took the role of Operations Manager.

Primary objectives in FY16 were to continue to provide:

- seed money for concept development
- DoD-wide experimentation programs,
- an education venue,
- a source of concept generation,
- and a DoD-wide forum for collaboration

The remaining sections of this report will address each of these objectives.

A. RESEARCH AND EXPERIMENTATION

At the direction of the SECNAV, NPS continued to leverage long-standing experience and expertise in the research and education of robotics and unmanned systems to support the Navy's mission. CRUSER continued to serve as a vehicle by which to align currently disparate research efforts across the NPS campus as well as among academic partners and the greater community of interest. Funding in FY16 was granted to projects led by NPS faculty members to explore many diverse aspects of unmanned systems.

In September 2015, CRUSER made its fourth call for proposals to seed research topics. The stated funding period was 1 October 2015 through 30 Nov 2016, and the funding levels were set at $75,000 to $150,000 per proposal.

At the beginning of September 2015, 42 proposals totaling over $4.7 million in requests were considered for CRUSER funding. The CRUSER advisory committee selected 31 projects, and granted $2.77 million in total to support their work in FY16 (*see Table 1*). All funded project summaries are included in this section of the report.

Table 1. FY16 CRUSER funded projects (alphabetical by principal investigator last name)

PROJECT TITLE	PRINCIPAL INVESTIGATOR
Expanding Unmanned System Networks for Littoral Operations using Projectile Based Nodes	Bordetsky
Integrating a Semantic-Web Ontology for Ethical Robot Tasking in AVCL to Create a Mission Test Suite using AUV Workbench	Brutzman
Network Optional Warfare (NOW): Optical Signaling and Data Compression for Improved Stealth	Brutzman
RoboDojo	Buettner/Tsolis
Electro-Optic Detection in Littoral for MIW/ASW Using Navy's EODES Model and Glider-Measured Optic Data	Chu
Low-Cost High Precision Aerial Delivery System (LC-ADS)	Dobrokhodov
Tethered AUV Operations from a Mobile Robotic Outpost	DuToit, Horner
Agent Modeling of Unmanned Systems Course Module	Giachetti
Educational Manuals for Monterey Phoenix	Giammarco
On the use of UxVs in Seabasing Cargo Transfer	Gordis, Kaminer
Quadrotor Unmanned Aerial Vehicles as Platforms for Atmospheric Measurements in Marine Environments	Guest
Phase II Robotics Grasping	Harkins
Autonomous Navigation in Polar Environments: ICEX16 Ice Operations	Horner
Short Range Wireless Power Transfer (WPT) for UAV/UAS Battery Charging – Phase III	Jenn
Low-Cost Expendable UAS with Application to Low Altitude Atmospheric Measurements	Jones, Wang

Glider Based Ambient Noise	Joseph
Optimal Intelligence Gathering and Defense Strategies against a Swarm Attack on a High Value Naval Unit	Kaminer
Sensor-Based Motion Planning for Marsupial MCM Teams	Kragelund, Horner
Non-RF Communications for Scan Eagle Unmanned Aerial Vehicle	Monarrez, Horner
Command & Control for Teams of Autonomous Systems and People	Nissen
Using Small Unmanned Aerial Systems as Electronic Warfare Platforms - Providing the Tactical Ground Commander the Electromagnetic Advantage	Pace
Stratified wakes induced by submerged propagating objects: detection using USVs and UUVs	Radko, Joseph
Characterization of the Arctic acoustic environment using unmanned mobile sources in ICEX-16	Reeder, Joseph
The "Manicopter": an Unmanned Aerial Multicopter Vehicle with Robotic Manipulation Capability	Romano, Yun
Data Farming Short Course Development for the CRUSER Community	Sanchez_DFW
Closing Capability Gaps: Data Farming Methods for New Concept Exploration in the CRUSER Community	Sanchez_Gap
Robotics System Software Engineering Case study	Shebalin
Real-time undersea networking using acoustic communications for improved UUV positioning and collaboration	Smith, Cristi
Enabling Secure Group Communications for UAV Swarms using Distributed Key Management	Thulasiraman
Tactical Aerial Resupply with Extended Standoff Range	Yakimenko
MATLAB Interface for Mobile Robots	Yun

Some of these projects are complete, and others were still in work as their period of performance ended on 30 November 2016. These research summaries include work as of 30 September 2016, are listed in alphabetical order by primary Principal Investigator (PI) last name, and each has a point of contact listed for further inquiry.

1. Expanding Unmanned System Networks for Littoral Operations using Projectile Based Nodes

The most broadly used advanced network systems currently in use for maritime networking with unmanned assets and for various types of ship-to-ship and ship-to-shore communications, are characterized by their robust and persistent usage of the space-time communications continuum. However, recent developments in both cyberspace and electromagnetic spectrum operations promise to challenge the military's ability to rely upon persistently connected networks. It is time to explore different networking options, beginning with different underlying assumptions. A few years earlier, Bordetsky and Netzer[1] proposed the concept of "networks that do not exist," that is, employing multi-medium networks whose connections do not persist in time and space, but connect only long enough to transmit critical information securely. Based on this type of unconventional approach, Bordetsky, Benson, and Hughes[2] conceptualized that the importance of such "hard to detect-hard to compromise" nodes for supporting the Littoral Combat Ship new mesh networking operational roles in the emerging clutter-filled littoral combat is becoming critical.

In this case, the LCS needed for the mission is a hub type, and it activates a network for data collection that doesn't exist, by shooting projectiles with mesh networking payloads. The payloads transfer surveillance data in burst transmissions received by the hub via periodic moments of cube satellite orbital node availability, unmanned surface vessels, fast patrol boats and unmanned ground vehicles, all in a coordinated dance. Within four to eight seconds, the projectiles recede from view, and the enemy only vaguely knows the general LCS location.

Hence, the objective for the described research project was to focus on designing a novel testbed environment and conducting a series of experiments for exploring new techniques of operating unmanned systems network via very short lived – four to seven seconds each – projectile-based nodes.

In order to meet the general project objective, the NPS CENETIX team focused the research effort on overcoming several major challenges. The first challenge to address would be to create a prototype of the robust networking payload which is capable of surviving the miniature

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[1] Bordetsky, A., & Netzer, D. (2010). "Testbed for Tactical Networking and Collaboration", International Command and Control Journal, Volume 3, Number 4Restech (n.d.). Retrieved October 12, 2016 from www.restech.no/products \

[2] Bordetsky, A., Benson, S., and Hughes, W. (2016). Hiding Communications in Plain Sight, SIGNAL Magazine, June.

projectile ascent- descent, and, desirably, even landing conditions. The second challenge to address would be to evaluate what type of mesh data networking such a short lived network is capable to support, and what are the ways to monitor it.

The CENETIX team is currently at the stage of completing prototyping the projectile payload and its launch. USMC Major Thomas Kline, IS/CENETIX thesis student and Senior Researcher Eugene Bourakov are currently prototyping the projectile-based networking nodes, as envisioned in earlier cited publications, to be launched by the ground combat grenade launchers or naval cannons.

Figure 2. Pneumatic Line Thrower (PLT).[3]

These nodes will soon be ready for launch trials using a Norwegian Pneumatic Line Thrower (PLT) depicted in Figure 2 and a gas-combustion system commonly known as a 'spud gun.' To enable such a trial Maj. Kline designed and printed the projectile bodies using SolidWorks 2016™, SketchUp Pro 2016™, and Ulti-Maker™ 3D printers provided by the NPS Robo-Dojo which is led by Kristen Tsolis. Maj. Kline plans to employ projectiles with altimeter-driven and accelerometer-driven parachute deployment systems in order to observe the impact of flight time in the node's ability to deliver the payload between disconnected network nodes. Figure 3 shows a current prototype with PLT.

[3] Retrieved from http://www.jgarraio.pt/index.php?main_page=product_info&cPath=1510&products_id=11364&subtemplate=mc&language=en

Figure 3. Projectile prototypes with parachute deployment system and stabilizer fins.

Series studies have been conducted to identify the appropriate miniature payload, capable of providing the projectile –based networking. The winning solution appears to be a combination of VE Mesh™ radios and the Arduino™ microcontroller board. In addition to joint VBSS networking trials with CENETIX, the VE Mesh™ had demonstrated[4] to “maintain control channel with mesh capability” surviving the grenade launch. In the payload solution it is implemented as a radio module for tactical mesh network formation within a short period of descending time – 10 to 15 seconds. The Arduino™ microcontroller board running ATMega328 processor monitors flight status to detect the right moment for parachute compartment latch opening and parachute deployment. Projectile body orientation sensor and barometric pressure and accelerometer sensors will feed the microcontroller with data for autonomous decision making. The payload’s prototype board is shown in Figure 4.

[4] Hardy, L., (2016) E-mail memo regarding video camera with VE-mesh board launched by grenade launcher, July 20.

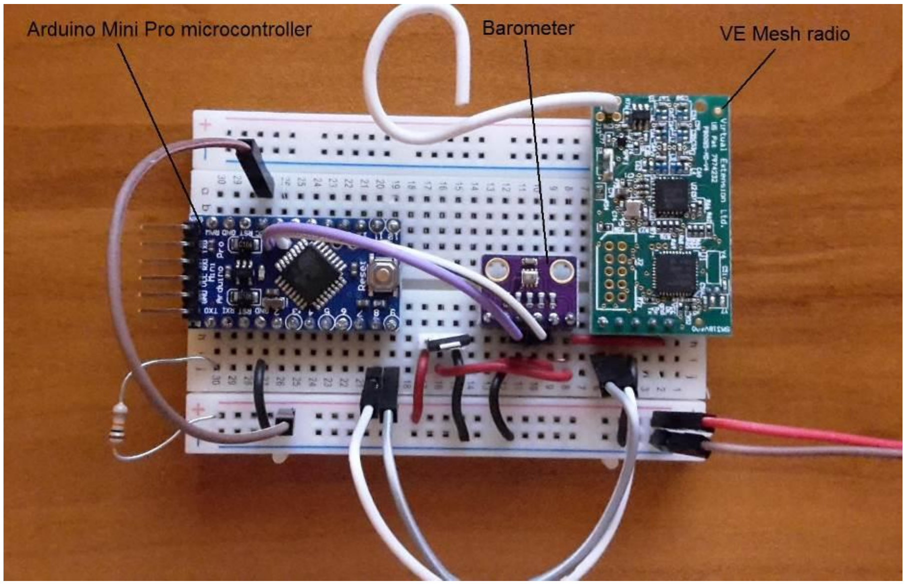


Figure 4. Payload prototype board.

The next step in the remaining time for this FY16 project, between now and the end of November is to conduct the series of PLT launched networking experiments with the described projectile node.

POC: Dr. Alex Bordetsky (abordets@nps.edu)

2. Integrating a Semantic-Web Ontology for Ethical Robot Tasking in AVCL to Create a Mission Test Suite using AUV Workbench

Military teams do not need robots that contain embedded philosophy software. They need unmanned systems that are reliable partners, carrying out approved tasks within limits and knowing when further guidance is needed. This project provides a solid theoretical and practical basis for tasking qualified robot systems with ethically constrained missions in human-system teams.

Many types of robotic vehicles are increasingly utilized in both civilian and military maritime missions. Some amount of human supervision is typically present in such operations, thereby ensuring appropriate accountability in case of mission accidents or errors. However, there is growing interest in augmenting the degree of independence of such vehicles, up to and including full autonomy. A primary challenge in the face of reduced operator oversight is to maintain full human responsibility for ethical robot behavior. Informed by decades of direct involvement in both naval operations and unmanned systems research, this work proposes a new mathematical formalism that maintains human accountability at every level of robot mission planning and execution. This formalism is based on extending a fully general model for digital computation, known as a Turing machine. This extension, called a Mission Execution Automaton (MEA), allows communication with one or more "external agents" that interact with the physical world and respond to queries/commands from the MEA while observing human-defined ethical constraints.

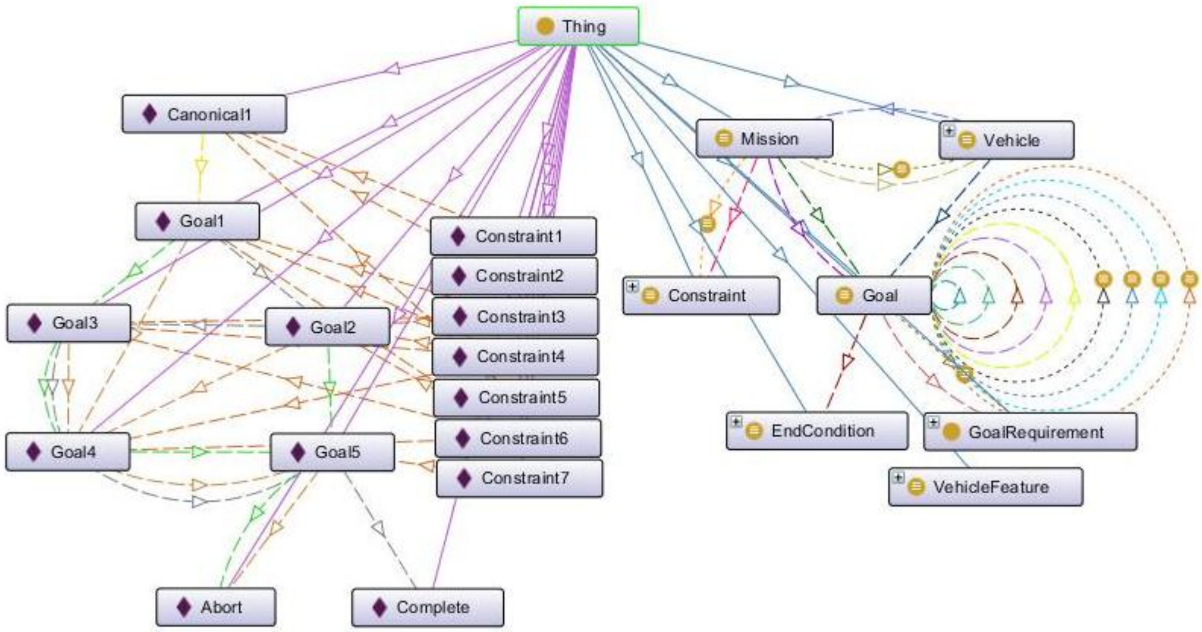


Figure 5. Web Ontology Language (OWL) diagram of goals, relationships, and ethical constraints shows how example missions can be formally validated for logical coherence and semantic correctness.

An important MEA feature is that it is language independent and results in mission definitions equally well suited to human or robot execution, or any arbitrary combination. Formal description logics are used to enforce mission structure and semantics, provide operator assurance of correct mission definition, and ensure suitability of a mission definition for execution by a specific vehicle, all prior to mission parsing and execution. Computer simulation examples show the value of such a Mission Execution Ontology (MEO). The flexibility of the MEA formalism is illustrated by application to a prototypical multiphase area search and sample mission. This paper presents an entirely new approach to achieving a practical and fully testable means for ethical mission definition and execution. This work demonstrates that ensuring ethical behavior during mission execution is achievable with current technologies and without requiring artificial intelligence abstractions for high-level mission definition or control.

POC: Dr. Don Brutzman (brutzman@nps.edu)

3. Network Optional Warfare (NOW): Optical Signaling and Data Compression for Improved Stealth

Naval forces do not have to be engaged in constant centralized communication. Deployed Navy vessels have demonstrated independence of action within coordinated operations for hundreds of years. Littoral operations, unmanned systems, and single-purpose ships pose a growing set of naval challenges and opportunities. Network-optional warfare (NOW) can be achieved through efficient communications, signaling stealth, and deliberate tactical messaging. The Navy RDT+E Strategic Cell has recognized the potential impact of these command and control (C2) operational concepts during development of the Navy RDT+E 30-Year Strategic Plan. Current work is focused on showing data-centric approaches for unmanned systems that provide important new options for warfighters.

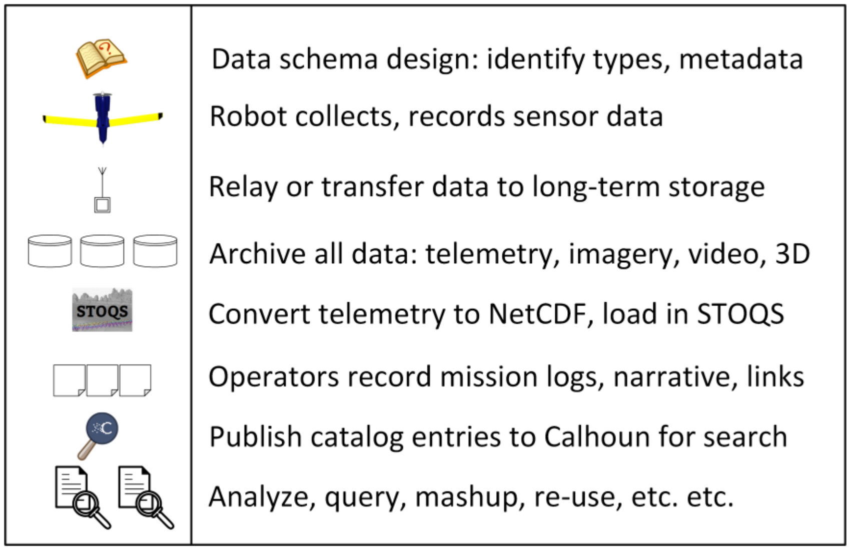


Figure 6. Robodata workflow converts raw data into structured datasets to provide queriable information for analysis.

The JIFX Robodata project is establishing NPS data-collection capabilities for a wide variety of unmanned system experiments. NPS performs many experiments with unmanned systems, but few projects are able record results in a systematic reusable way. Utilizing open assets in a repeatable, sustainable way can build an institutional archive of worthy examples that is easy to adopt. Initial implementation efforts are establishing NPS data-collection capabilities for unmanned system experiments. Utilizing open assets in a repeatable, sustainable way can build an institutional archive of worthy examples that is easy to adopt.

The inability to access, compare and re-use unmanned system data is a widespread shortfall, so the team is working to build a lasting foundation. Much future work is expected. Linking searchable experiment metadata from recorded archives with the Dudley Knox Library's Calhoun institutional archive can ensure that results are discoverable and re-usable. A properly accessible system will providing regular support for course and thesis work by NPS students and faculty. A design-based approach can support NPS course and thesis work for students and faculty. Emerging robodata archives will be used to show that integrating XML-based compression, digital signature, and encryption can make unmanned systems less vulnerable and more flexible for Network Optional Warfare (NOW).

POC: Dr. Don Brutzman (brutzman@nps.edu)

4. RoboDojo

The RoboDojo is an open-community venue where "tinkerers" of all abilities –from novice hobbyist to expert researcher – can converge and have access to a rich array of tools, space, and hands-on training to conceive, design, fabricate, implement, and observe the creation and integration of robotics technologies. The vision of RoboDojo is to empower the robotics generation through an open community venue for robotics exploration, innovation, and realization. The mission is to offer a communal and open environment for the extended NPS family to enhance its exposure to robotics across all backgrounds and disciplines through hands-on experiences and informal learning in robotics.

The RoboDojo officially opened its doors in July of 2015, and students and faculty from all departments on campus have visited the NPS campus facility and attended workshops. Since the July opening, the RoboDojo has hosted 12 visiting classes, regularly hosted four classes, and have held 80 workshops and user groups. Workshop topics range from robot programming and 3D modeling to Arduino / Raspberry Pi projects and laser cutting. The program has seen a steady increase in the number of people benefiting from the lab and its resources.

Figure 7. Workshops in the RoboDojo in FY16: Arduino Microcontroller (*top*) and Raspberry Pi (*bottom*)

Building on successes from last year, the team has further integrated the lab into the design thinking efforts on campus. The RoboDojo has proven to be a valuable resource for students learning to conduct graduate level research. Students have integrated their classroom instruction with RoboDojo resources to construct gliders, rockets, satellite and drone components, and many other robotic elements for field experiments at Camp Roberts, China Lake, and the Mojave Desert to name a few. RoboDojo hosted a glider design challenge in the lab and are currently hosting a series of classes that teach students how to construct and control Ant Weight Battlebots. The Ant Weight Battlebot competition is schedule for 16 December 2016, and all of the design, prototyping, and fabrication sessions are being conducted in the RoboDojo.

All of these focused workshops require a small investment of time but have the ability to have a high impact on students who may not have access to the equipment and the types of expertise offered in the lab. Another benefit of these open campus workshops is that they bring together students from multiple disciplines and backgrounds, and there is ample opportunity for cross-pollination and collaboration.

Figure 8. Rocket Design students (*top*) and Ant Weight Battlebot construction (*bottom*)

The base budget provided by CRUSER has functioned as a force multiplier. Now that the RoboDojo has hosted enough events to gain visibility and to foster a base of savvy users, the program has grown its abilities to reach out to the NPS community and to increase community knowledge regarding robotics and electronics. The goal for the coming fiscal year is to host additional robotics challenges in the lab, but the team would welcome other suggestions or offerings that organically grow out of community interest.

The Cebrowski Institute has contributed funding for computer science-related workshop gear, and the NPS Foundation has contributed funds for the Ant Weight Battlebot competition and the School of International Graduate Studies (SIGS) at NPS has helped to fund efforts supporting international students. The RoboDojo is seeking to further broaden its network to ensure the entire campus is best served by a true community resource promoting and augmenting graduate level research.

POC: Professor Kristen Tsolis (ktsolis@nps.edu or robodojo@nps.edu)

5. Electro-Optic Detection in Littoral for MIW/ASW Using Navy's EODES Model and Glider-Measured Optic Data

This research project implemented the Navy's Electro-Optic Detection and Simulation model (EODES) for the Yellow/East China Seas. The depth-dependent attenuation and volume scattering coefficients are computed from the glider observed optical profile data. The EODES model used optical data originated from the Slocum glider to estimate LLS performance prediction under the observed optical environment. The raw glider data have been processed to produce depth casts of optical properties, and these depth casts are input into EODES model to produce a performance prediction map of the operational area: Green = High Probability of Identification (PID), Yellow = Medium PID, Red = Low PID) at the position of each depth cast that provide an estimate of LLS performance at the time of the cast.

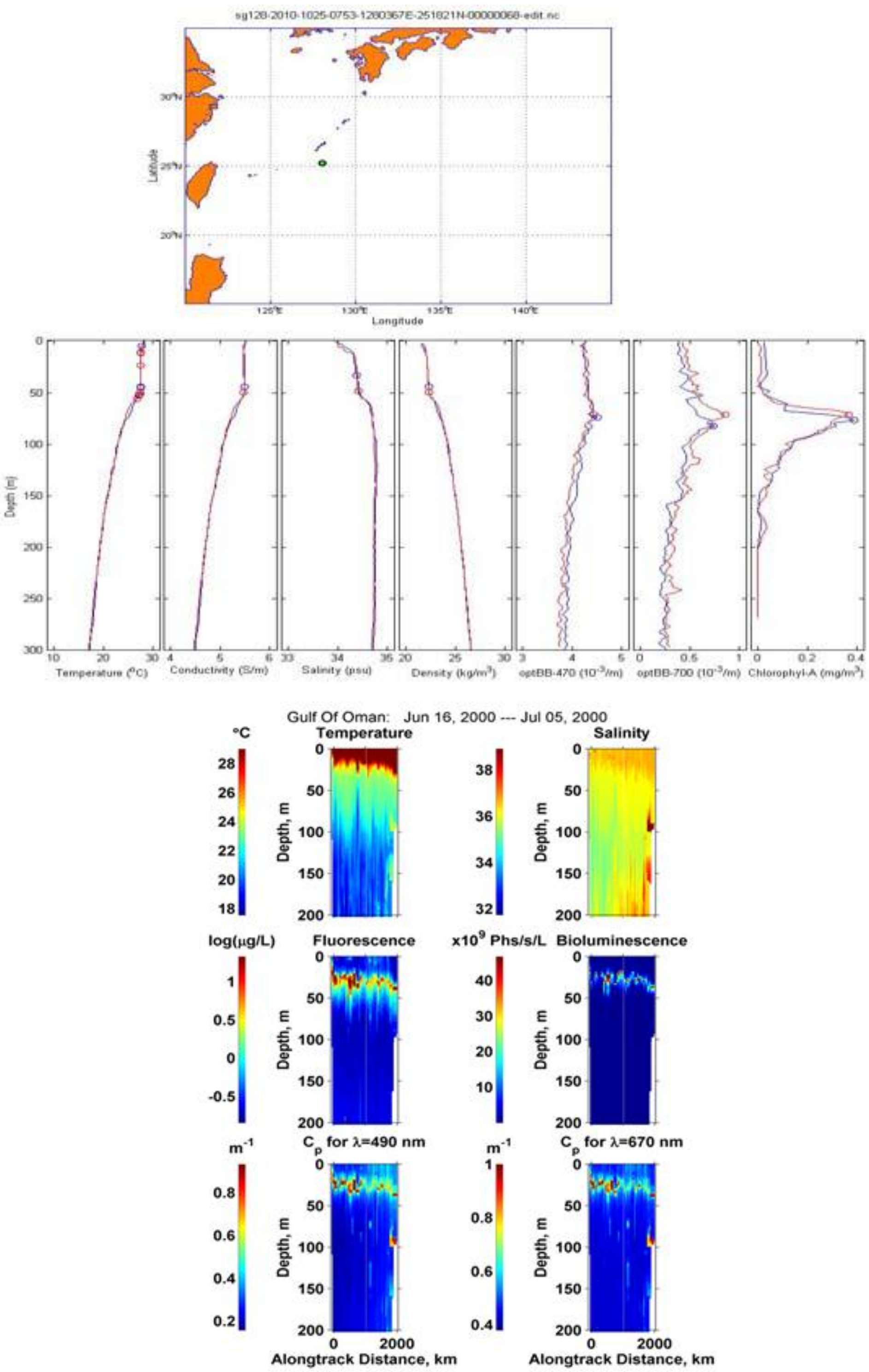


Figure 9. Relationship between underwater optic and hydrographic data (top) Yellow/East China and (bottom) Gulf of Oman

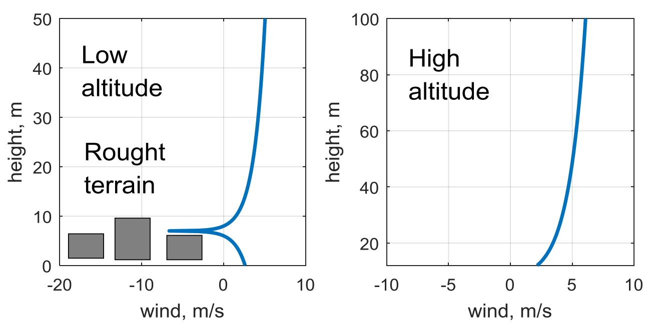
Relationships between hydrographic and optic parameters have been established with examples from the Yellow/East China Seas and Gulf of Oman (*see Figure 9*) between (T, S) and optic parameters (backscattering coefficients and chlorophyll-a concentration). The depths of maximum backscattering coefficients and chlorophyll-a concentration are below the ocean mixed layer. Statistical module has been developed from the existing NAVOCEANO glider profile data (more than 20,000) for the Yellow/East China Seas to predict optical variables such as light transmissions, backscattering at different light wave lengths using hydrographic variables such as the temperature and salinity.

POC: Dr. Peter C. Chu (pcchu@nps.edu)

6. Low-Cost High Precision Aerial Delivery System (LC-ADS)

The project addresses the precise delivery of small – one to two pound – payloads to remote locations at a very low cost using several operational approaches to satisfy the payload restrictions of a particular mission. The considered methods include: 1) the release of a small, very low-cost, steerable store, 2) the remote landing of a low-cost, expendable UAS with possible self-destruction, and 3) the remote landing and relaunch of a low-cost UAS enabling reuse of the asset as well as two-way payload delivery. The key technological challenges addressed by the project are (i) the large distance to remote location, (ii) the very short duration of the delivery trajectory (~5 sec), and (iii) the presence of an uncertain wind profile that diverts the descending payload away from the desired location. Large distance of operation is dictated by the minimal acceptable utility of the autonomous platform. Short duration of the descent trajectory is dictated by the need to fly below radar, as well as minimizing the impact of wind on the guided store. The lifesaving urgency of the payload delivery to a remote location and the above mentioned challenges significantly differentiate the low altitude delivery task from all existing approaches thus justifying the novelty of the project.

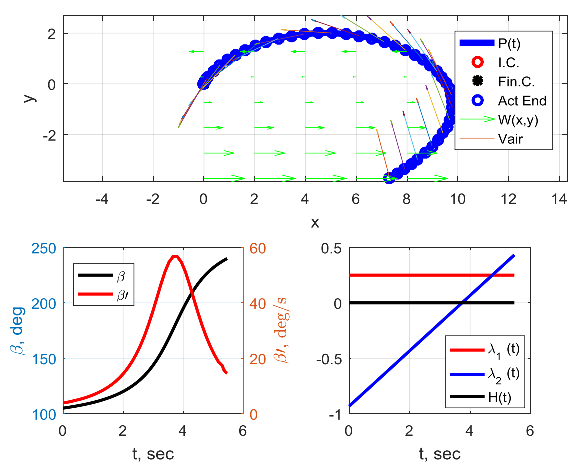
The project evolves in two primary directions including the hardware and software developments which intend to utilize a cheap UAV platform that is already under development for other Navy projects; solar powered and the swarming UAV projects are the key developments to be leveraged on.



The remote landing approaches require flight algorithms that minimize landing errors in the presence of wind uncertainty as well as allow for potentially large shifts in the aircraft weight. The *optimal path planning* and the *wind estimation* algorithms are the key components here.

Design of the aerodynamically stable capsule and of the release mechanism is the key hardware development efforts of the project.

The *wind estimation* algorithm adopts the logarithmic law (1) $u = \frac{u^*}{\kappa} \ln(\frac{h - h_0}{z_0})$, which accounts for the aerodynamic roughness length z_0 (characterization of terrain roughness including urban environment) and the displacement height h_0 (AGL height at which zero wind speed is achieved as a result of flow over obstacles such as trees or buildings) in the target zone, where *u*- is the mean wind velocity at *h*- the UAV height, u^* is the friction velocity (velocity scale or shear), is the von Karman constant (0.4). The log wind profile is generally considered to be a more reliable estimator of mean wind speed than the power law in the lowest 10–20 m of the planetary boundary layer. Small number of key parameters enables rapid online identification of the vertical wind profile in a short time of 2-3 spiral orbits (40-80 sec) above the target. The approach utilizes a plethora of works of Planetary Boundary Layer (2) that further simplifies online calculation by parameterizing the equation as follows; u^* lies in range of 0.05 to 0.5 m/s; z_0 - 10% of mean prevailing height of a building; h_0 – 70% of mean canopy height. Utilizing the parameterization of vertical wind profile and the onboard measurements (ambient air temperature, height, magnitude of airspeed, and the speed over the ground) enables its rapid recursive evaluation that enters the optimal guidance.



The optimal guidance method minimizes the time and the control effort of delivering the UAV into the terminal point in the presence of given wind profile that is estimated online in the vicinity of the target zone within the "surface layer". The approach is based on the Pontryagin maximum principle that minimizes time and/or the energy effort required in terminal guidance phase. The task is formulated as the two point boundary value problem for a point mass vehicle that needs to be transitioned optimally from a given initial to the desired final location in the presence of known wind profile; time-varying wind profile case is also solved and needs an extension of the parameterized wind model to account for short scale time variations. An example of the 2D perspective of optimal path for an analytically defined wind profile is presented next; the optimality of the path is confirmed by the constant and zero value of Hamiltonian ($H(t)$).

In the case of the dropped store, the above discussed solutions of the online wind estimation and the optimal guidance are adopted. The key difference lies in calculating the optimal release point of the capsule that has reduced aerodynamic control authority. The computational speed of the optimal control implementation is measured by ~0.01 seconds and relies on the commercial boundary value problem solver provided by MathWorks.

The flight hardware for the delivery system is the Penguin UAS. NPS has an IFC for the platform and has made a number of flights with the airframe to tune autopilot gains and characterize the performance. The low-cost airframe is about $900 with all hardware required for autonomous flight. The airframe can utilize a variety of battery packs depending on the desired endurance/payload. With the maximum currently rated battery, flight times of over 60 minutes are possible, with cruise speeds of 30-40 knots.

Hardware for the steerable dropped store has been acquired. Drawing from the racing-drone community, a low-cost, open-source flight controller is combined with a pair of micro 9g servos and single-cell LiPo with up-converter. Laser-cut foam-board, cut EPP foam and printed airframe variations are in the works. Initial models will be RC-only to avoid IFC requirements for rapid design iterations. All up cost of the steerable dropped store should be about $50.

The following is the summary of the deliverables to date:

1) The wind estimation mechanism and the corresponding algorithms.
2) The path planning algorithm for optimal guidance in the presence of wind.
3) Implementation of analytical models in MatLab.
4) Sensitivity analysis studies that verify feasibility and performance of guidance and wind estimation algorithms.

POC: Dr. V.N. Dobrokodov (vldobr@nps.edu), Dr. K.D Jones (jones@nps.edu), and Dr. I.I.Kaminer (kaminer@nps.edu)

7. Tethered AUV Operations from a Mobile Robotic Outpost

Autonomous Underwater Vehicles (AUVs) have not yet reached their full potential for undersea warfare operations. Current AUVs (and unmanned systems more generally) require launch and recovery and logistics support from manned surface platforms (e.g., LCS). In combat zones or contested areas, these manned platforms must operate in harms way, which requires additional manned assets for force protection, command and control, air support, etc. The logistics tail required to support unmanned operations in dangerous areas can quickly defeat the purpose of going unmanned in the first place. Thus, before naval forces can fully leverage autonomous vehicles in support of the wide-area, long-duration missions characteristic of undersea warfare, it is necessary to break the tether between the robot and its support by manned platforms. One concept for achieving increased persistence without burdening manned support vessels is an "undersea garage," or robotic outpost.

This research furthered the concept of a robotic outpost by focusing on tethered AUV operations from a mobile robotic outpost. The research focused on developing capabilities for operating the ACQUAS hovering-capable AUV from a surrogate platform and to execute an autonomous mission. In addition to furthering the robotic outpost concept, this capability has closer-term operational analogs in the NSW community (e.g., operations from the SEAL Delivery Vehicle, SDV), the submarine community (e.g., inspections and intervention from a submerged submarine), and envisioned LDUUV use cases.

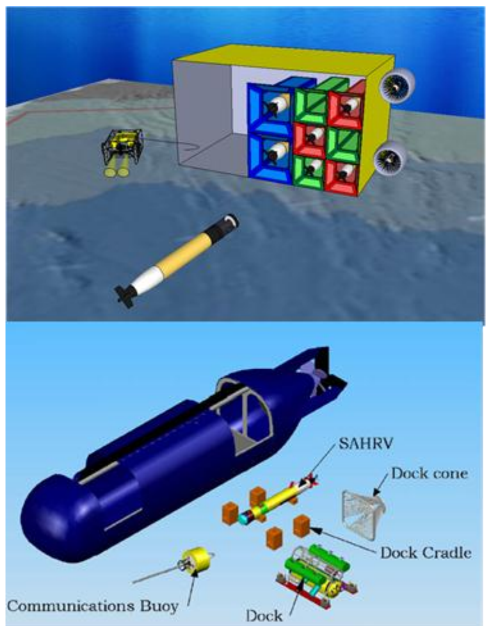


Figure 10. A self-sustaining robotic outpost provides power, communications, and navigational aiding infrastructure to heterogeneous AUV assets, while providing an intervention, inspection, and maintenance/repair capability.

a. Executed Tasks

Researchers at CAVR have developed a hovering AUV capability for close-quarter operations (i.e., close to structures, other assets, or divers). This well instrumented platform, based on the SeaBotix vLBV300, has been outfitted with GPS, an Inertial Navigation System (INS), Doppler Velocity Log (DVL), high-definition camera, forward-looking SONAR, and an unarticulated grabber. This small, highly maneuverable platform has five controllable degrees of freedom (surge, sway, heave, roll, yaw).

The prior results in Adaptive Control on ACQUAS were extended in this investigation. First, the update rate from the INS was increased to facilitate faster adaptation in the control algorithm. This worked well in simulation, but the results could not be reproduced on ACQUAS. Upon further investigation, it became clear that the implementation of the underlying hardware upon which ACQUAS is built has significant limitations. These stem in part from low-update motor controllers in the thrusters, and a non-deterministic sequential distribution of the control signals to the thrusters. Thus, the physical limit of the hardware was reached. Furthermore, a new platform will be coming to market soon that does not have similar constraints, so this research was halted.

Proximal operations require accurate knowledge of the vehicle position and the environment. However, the localization solution of an AUV normally relies on relative measurements (i.e., velocity measurements from a DVL and acceleration/rate measurements from an INS). These measurements are susceptible to bias, causing the position estimate of the vehicle to drift. Above-the-surface platforms rely on GPS for an absolute measurement. Historic approaches to underwater localization such as acoustic beaconing systems (e.g., Long Baseline Systems, etc.) provide accuracies on the order of meters, which is not sufficient during close-proximity operations (i.e., navigating into a net for AUV recovery). Close-proximity operations afford new opportunities for Terrain Relative Navigation (TRN) approaches (i.e., tracking the AUV position relative to the environment). The ability to track specific static features or objects in the environment provides a spatially fixed measurement to the AUV, even if the exact geo-referenced location of that object is unknown.

Sonar-based Visual Odometry was investigated as a navigation aid when the platform is executing slow-movement tasks (e.g., hovering). Historically, these approaches have been less-than-satisfactory since the sonar resolution is low, update rates are small, and relative motion between successive pings are large. The sonar used in this research (the BlueView MB2250) is a high-frequency sonar, resulting in a relatively high update rate and higher resolution image. Moreover, the platform motion between successive pings is small due to the nature of the AUV platform.

A Least-Squares approach was developed that averaged the detected motion in successive images while accounting for the non-linear mapping from linear and rotational motion to the sonar image. By averaging the detected motion, the method proved useful for estimating the small relative motions during hover mission. These measurements can be used in conjunction with, or instead of, DVL measurements (which tend to drift over time). This sonar-based visual odometry is also different from feature-based navigation in that specific features are not identified and tracked over time, but instead many (pixel-level) features are tracked between successive pings.

b. Experimentation Program

Since 2013, CAVR has participated in the NASA Extreme Environment Mission Operations (NEEMO), which takes place at Aquarius Underwater Habitat off Key Largo, FL (*see Figure 11*): Astronauts (referred to as Aquanauts in this context) execute an extended subsurface mission to develop the desired skills and familiarity with technologies. This collaborative effort between CAVR and NASA Johnson Space Center (JSC) allows for significant cost sharing: CAVR can leverage the operational support provided by NASA for NEEMO to test and demonstrate ongoing research efforts in realistic, ocean-based experiments at a fraction of the cost. At the same time, NASA can focus on their operational challenges and objectives by leveraging existing and ongoing underwater technology development at CAVR.

Figure 11. Aquarius habitat, off Key Largo, FL

CAVR participated in NEEMO 21 in July, 2016 with ACQUAS as well as 2 REMUS AUVs. Data is still being processed, but REMUS operations were very successful. Unfortunately, ACQUAS operations were plagued by hardware failures and poor environmental condition. The platform was updated to include an HD video capability. This capability proved to be extremely useful during ICEX2016 in March 2016, and also at the start of NEEMO 21. However, the routing of the fibers in the tether at the connection with the platform by Teledyne SeaBotix proved to be fragile. Two fibers were lost during operations in rougher-than-usual seas. Thus, the capabilities developed for this program could not be tested to the extent necessary. A follow-on test opportunity will be pursued once the platform has been repaired.

POC: Dr. Doug Horner (dphorner@nps.edu)

8. Agent Modeling of Unmanned Systems Course Module

For a project summary please contact this researcher directly.

POC: Dr. Ron Giachetti (regiache@nps.edu)

9. Educational Manuals for Monterey Phoenix

Beginning in 2015, CRUSER sponsored the development of the Monterey Phoenix approach and language to help identify failure modes and corresponding failsafe behaviors in unmanned systems. The MP analysis capability has since moved beyond the confines of an NPS-internal "breadboard" development environment, and onto the World Wide Web at http://firebird.nps.edu, accessible to the entire CRUSER community through an easy to use GUI and trace visualizer. Supplying the tools and documentation for no less than six Master's theses and two PhD dissertations completed and published between 2015-2016, MP has now demonstrated its utility in a variety of unmanned systems problem spaces, has stirred excitement and interest among NPS students, and has matured to the point where it is ready for mainstream application and use to advance unmanned systems design throughout the Navy.

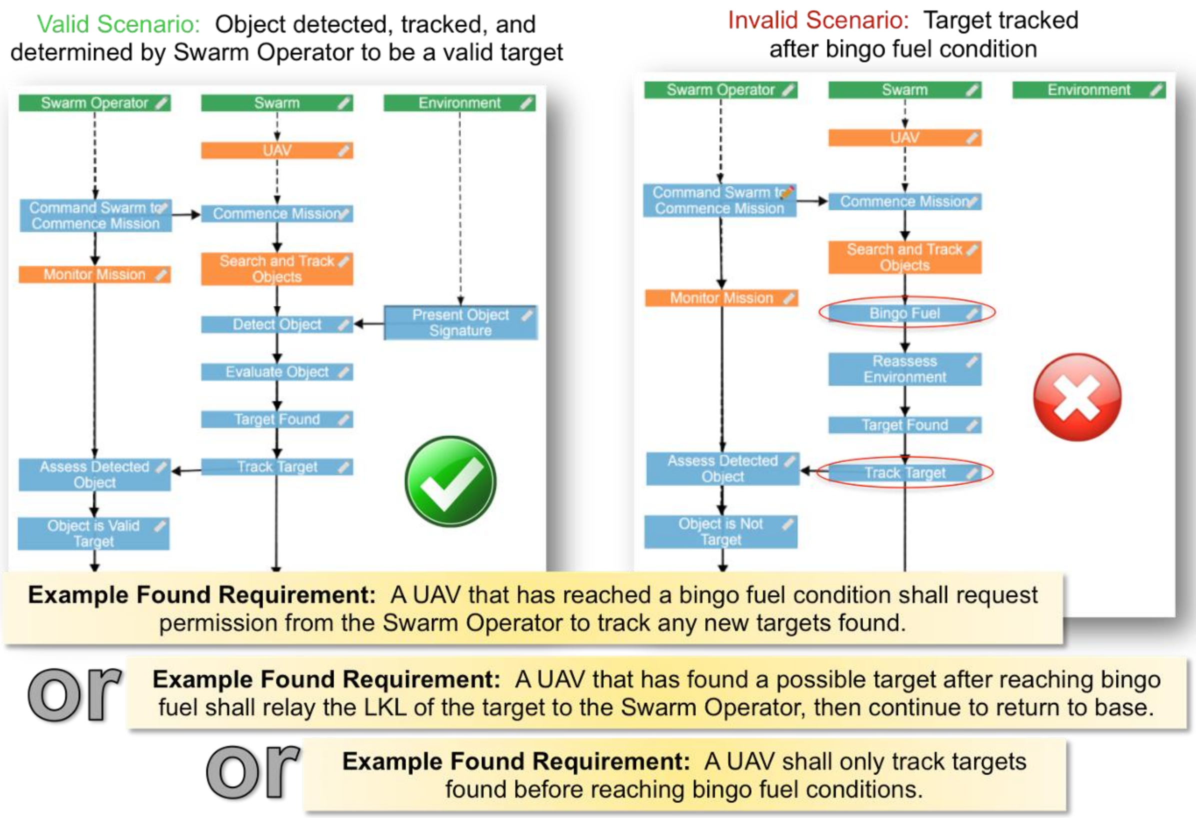


Figure 12. Monterey Phoenix education manual sample.

MP is a systems engineering approach and tool with a demonstrated ability to expose incorrect, hazardous, or otherwise undesirable behaviors in processes and system designs so that these unwanted behaviors (such as failure modes) can be removed or mitigated before they manifest in an actual system. An exhaustive set of automatically generated scenarios contains all behaviors, including potentially undesired behaviors that may have otherwise remained undiscovered. The MP approach allows a far greater scope of V&V to take place early in a system's lifecycle, compared with long-established methods, processes and tools in current use throughout government and industry. Educational manuals and other documentation has been developed in 2016 in order to make MP accessible to others in the CRUSER community and beyond.

Researchers and practitioners can now use MP with accompanying documentation to:

- better understand and test requirements in the context of environment behaviors and interactions with the system
- expose system behaviors using executable models, before they build / fly them

- automatically generate an exhaustive set of use cases
    - humans understand examples better than generic formalisms
- recognize errors/deficiencies early and reduce system development cost
- automate testing and verification of models using exhaustive, systematic testing with assertion checking
- enhance and extend existing modeling methodologies and frameworks, providing far better coverage of scenarios to be rendered in UML, SysML, EFFBD, and DoDAF views

By far the most notable achievement over 2015-2016 was the demonstration that MP can expose unexpected "failure mode" scenarios that were not foreseen by the MP modelers in each case. For example:

- A swarm of unmanned aerial vehicles on a search and track mission reaches a return-to-base condition, correctly begins its egress, but then finds and begins to track a new target. (Revill 2016)
- A first responder administers medication to an unconscious patient, unaware that the medication has already been administered. (Bryant 2016)
- A supply spacecraft approaching to dock with the International Space Station continues its approach despite the presence of a known hazard condition. (Nelson 2015)
- An IT system enters an indeterminate state after a transaction is canceled. (Pilcher 2015)

In exposing these behaviors in simulation, requirements can be modified to prevent or mitigate these scenarios from actually playing out in later lifecycle phases of the system. For example MP models of unmanned systems, and to obtain the educational manuals and other project deliverables, please visit wiki.nps.edu/display/MP or contact the project POC.

POC: Dr. Kristin Giammarco (kmgiamma@nps.edu)

10. On the use of UxVs in Seabasing Cargo Transfer

The transfer of cargo in seabasing, both in the assault phase and sustainment phase involves a network of ships, connectors, and land bases. The evolution of unmanned vehicles, points to their potential role in seabasing cargo transfer. The objective is to evaluate the use of UxVs (Unmanned Air/Surface/Underwater vehicles) as connectors in the resupply network. In particular, this research team is interested in analyzing re-supply operations in the combat zone where the probability of loss of unmanned cargo delivery systems is substantial. A cargo transfer network modeling software is being adapted for this purpose. The network modeling software is being used in conjunction with a stochastic dynamic model for weapons effectiveness which predicts loss of aircraft. This first phase of research is an open-loop investigation of the effect of loss of UAVs due to operations in combat zone on cargo transfer network throughput.

To date, the cargo transfer network modeling software has been modified for this purpose. A graphical user interface has been developed to allow convenient creation of the network model. The scenario modeled for this initial work is based on a number of AAV whose characteristics are based on the V-22 Osprey. The baseline scenario involves 10 AAV, traveling a distance of 300 nm, at a speed of 200 kn, tasked to deliver a total cargo of 1000 ton. The payload of each AAV is 5 ton. In addition, this research team developed a numerical tool that determines probability of a loss of a cargo UAV to enemy fire. It explicitly accounts for the kind of defensive weapons used and for the number of hits a UAV can sustain before its complete loss. The next step is to integrate both tools to provide the mission planner with a better estimate of the number of cargo UAVs required for a particular sea-basing cargo re-supply mission.

POC: Professor Joshua Gordis (jgordis@nps.edu) and Dr. Isaac Kaminer (kaminer@nps.edu)

11. Quadrotor Unmanned Aerial Vehicles as Platforms for Atmospheric Measurements in Marine Environments

This research involved the development of an atmospheric measurement system using standard radiosondes (instruments normally used on weather balloons) attached to an InstantEye Quad-rotor unmanned aerial system (UAS), manufactured by PSI Inc. This research addresses a current gap in the Navy's ability to characterize the lower atmosphere, especially with regard to Electronic Maneuver Warfare and in particular the effect of the atmosphere on the propagation of electromagnetic (EM) radiation.

In previous years, this team successfully demonstrated the feasibility of this system with a series of tests at Camp Roberts, California. As part of these tests the team flew the UAS alongside a tower with calibrated measurements of pressure, temperature and humidity. Demonstrated by this research, this UAS/radiosonde system could measure mean atmospheric parameters with better resolution and accuracy than a standard radiosonde and was particularly useful at characterizing low level features such as the "evaporation duct" that can have major impacts on Navy EM systems such as radar.

Figure 13. Dr. Peter Guest flying the InstantEye UAS with radiosonde over Arctic sea ice. (Photo by Byron Blumquist)

This year, the focus of the research shifted to marine operations, and included both basic and operational research. To support basic science research objectives, this research project successfully performed potentially the first multi-rotor UAS meteorological measurements over the frozen Arctic Ocean (*see Figure 13*). The UAS/radiosonde was a valuable tool for quantifying heat loss from leads and polynyas (open water areas in the ice pack), quantifying lower atmospheric structure and resolving changes in atmospheric structure across the edge of the ice pack.

To further test the feasibility of using this system to address operational Navy needs, this research project also incorporated UAS flights during three cruises just outside the Monterey Bay on a small research vessel (R/V John Martin) 25-27 August 2016 (*see Figure 14*). This research demonstrated the ability to launch and recover the UAS in a small deck space on a rocking vessel and perform meteorological measurements from inches above the ocean surface (adjusting flight altitude for ocean swell) to at least 1000 ft elevation. This shows that similar measurements could be performed from US Navy vessels on a routine basis.

Figure 14. The InstantEye UAS/ radiosonde flying over the Pacific Ocean, generating small waves. The InstantEye is about 1 foot across and is hovering about 18 inches over the ocean surface. (Photo by Tom Murphree)

This research has matured to the point where major CRUSER support will not be required in the future. As it progresses, this research will continue to need CRUSER support for obtaining interim flight clearances and meeting other safety and battery-usage requirements for future planned field programs, but major salary and logistics support for this research has been transitioned to other funding agencies such as the ONR Arctic and Global Prediction Program and the NSF Office of Polar Programs. This research demonstrates how the CRUSER program can enable a researcher with little aeronautical or engineering background (e.g. Guest) to successfully develop a UAS-based measurement system that has proven to be very useful for basic science research and has the potential to change the way the Navy collects environmental data and improve its Battlespace Awareness capabilities.

Several reports and presentations concerning this research are available upon request. In addition, a local Monterey Newspaper article and two professionally-produced videos concerning this research are available:

- Monterey Herald: http://www.montereyherald.com/article/NF/20160116/NEWS/160119813
- NPS Video (YouTube): https://www.youtube.com/watch?v=2HMepUeHrcg
- CRUSER Tech Talk: http://www.nps.edu/video/portal/Video.aspx?enc=FZfWNdpJ8Arj2%2bzG7DCgkBDax%2bOkpxH%2f

POC: Dr. Peter S. Guest (pguest@nps.edu)

12. Unmanned Systems: a Lab-based Robotic Arm for Grasping Phase II

Phase II continues the Robotic Arm Research conducted by Physics students during Phase I of this Cruser sponsored project. The resistive flex sensor glove, used to mimic JACO three finger effector motion, was replace with a Leap Motion Detector/Controller. The objective was to demonstrate real time control of the 6 DOF Jaco arm via the Leap Controller. The desire was to create an intuitive and adaptive system where the trajectory motion emulates human hand movements while grasping for objects. To achieve this, the kinematics and dynamics of the robotic arm were explored in a controlled lab environment for various predetermined tasks under Leap motion control.

Jacinto, in prior work, successfully demonstrated standalone Kinova Joystick operation but was unable to interface the Jaco arm with the glove controller. Palacios' intermediate approach characterized Jaco arm performance capabilities for various lift objects in cyclical tasks. Here, the research team designed C++ algorithms in the Kinova SDK environment and successfully interfaced with the Jaco Arm in close to real time. Testing on the Jaco arm, under Leap control, was fulfilled for different tasks.

Long term objectives for this project include Jaco arm integration with autonomous platforms for remote teleop control in difficult operational environments.

POC: Dr. Richard Harkins (rharkins@nps.edu)

13. Autonomous Navigation in Polar Environments: ICEX16 Ice Operations

Due to environmental changes, monitoring of the Polar Regions is becoming increasingly strategically important. It is challenging to persistently monitor these regions in a relatively cost effective manner. One way to accomplish this is through the use of unmanned autonomous vehicles. Once every two years, for the last 30 years, the Navy conducts an ice exercise (ICEX) in the Arctic Circle. For 2016 it was locate in the Beaufort Sea, 200 miles north of Prudhoe Bay, AK. The emphasis this year was on unmanned systems. The Center for Autonomous Vehicle Research (CAVR) CRUSER funded initiative was to bring unmanned aerial and underwater vehicles to ICEX16 to conduct science and research in collaboration with the NPS Oceanography department in the harsh arctic environment.

The research effort emphasizes six different elements. They all relied on the fundamental capability of how to deploy, recover and navigate unmanned systems in these extremely challenging, cold conditions. The initiatives include:

- Ice flow movement estimation for accurate AUV navigation
- Upward-looking sonar-based terrain relative navigation
- Autonomous search and identification of objects of interest in an ice flow
- Velocity estimation with an upward looking Acoustic Doppler Current Profiler

- Assessment of acoustics beacon systems for long baseline and ultra-short baseline navigation.
- Measurement of ice thickness with cooperative AUV/UAV navigation

Figure 15. ICEX 2016 Camp Sargo

The ICEX base, Camp Sargo, was on a moving ice flow. The camp included an airfield and temporary structures for housing up to approximately 60 personnel (*see Figure 15*). The ice flow moved up to 24 nm miles each day (*see Figure 16*). A map of the Camp Sargo trajectory is given in figure two. This presented a unique navigational challenge for the AUVs.

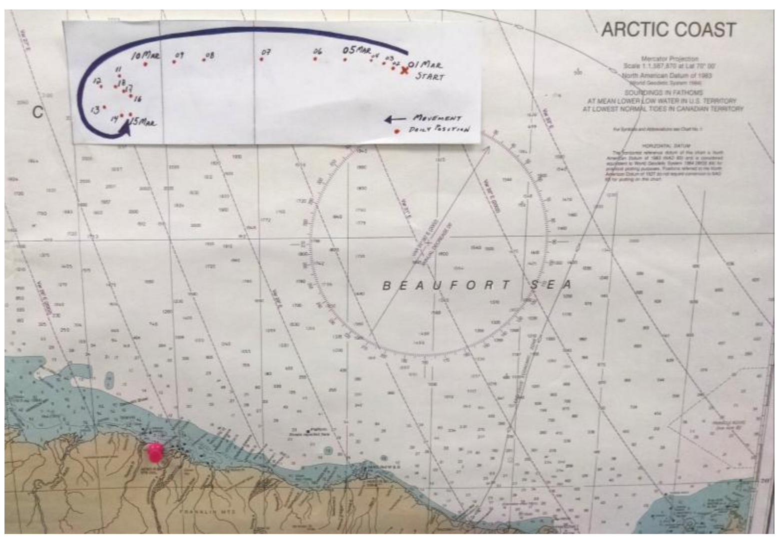


Figure 16. Movement of Camp Sargo through the duration of ICEX 2016. Red marks indicate position, the blue arrow give a summary of the motion through the entire exercise.

Normally, the vehicles assume that the ground is fixed – a point of reference provides a stable global navigational reference through constant GPS fixes. On a moving ice flow, this is no longer an accurate assumption. During ICEX, the ACQUAS AUV was able to navigate to a fixed, relative navigational framework. This was accomplished by tracking the pose (position, velocity and orientation) of the ice flow and subtracting it from the navigation estimate of the

AUV. This creates a local framework that simplifies navigational objectives such as statically holding position relative to the ice hole or navigating a series of waypoints that are fixed relative to the above ice.

A second area of concern was the ability of the Acoustic Doppler Current Profiler (ADCP)/Doppler Velocity Log (DVL) to function properly. The sensor measures vehicle and current velocities and is critical for undersea position estimation of robots. Normally the DVL faces downward, but because of the ocean depth (12,000 ft) this was impossible. Instead the DVL was pointed upward. This can be problematic since, with smooth ice, the sound can reflect away from the AUV (This was a problem encountered during earlier testing at Pavilion Lake). Testing at Camp Sargo showed that the roughness of the under ice provided the ability to provide accurate velocity estimates with an upward looking DVL.

The REMUS AUV was deployed 6 times. Each time a Long Baseline (LBL) was deployed to provide a local navigation framework. In addition, the normally autonomous vehicle was tethered to ensure that the vehicle could be reliably recovered. Prior testing in Monterey Bay showed that this was possible without seriously impacting the navigational accuracy. The REMUS performance was poor (*see Figure 17*). First the REMUS was unable to obtain a position fix using the LBL. Preliminary analysis shows that that AUV didn't not accept position fixes because of the ice flow motion interfered with the static position estimate that was received by the LBL.

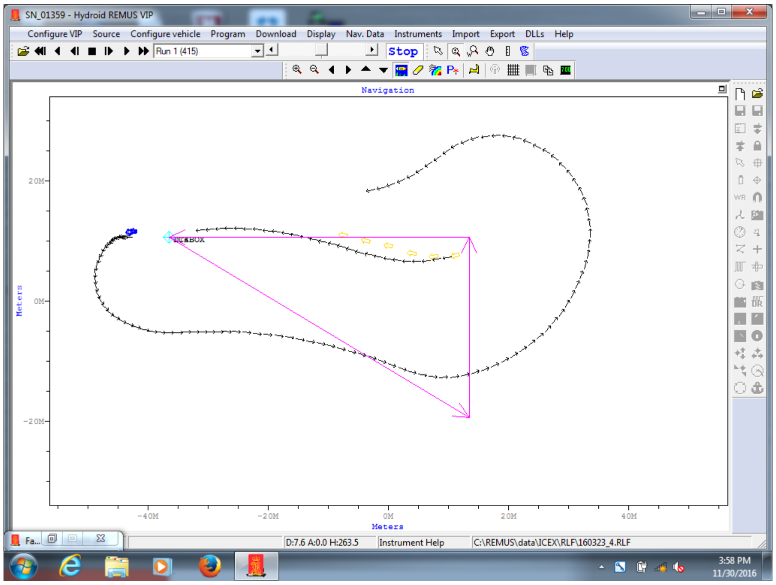


Figure 17. The image is an example of one of the REMUS mission runs during ICEX16. The intended track is in pink. The blue arrows are the GPS position estimates with the AUV at the ice hole. The dead reckon estimate of the AUV position is annotated with the black arrows. The jump in position toward the end of the mission is due to the new position estimate based on the USBL range and bearing measurements to the ice hole transponder (The valid USBL measurements are the arrows in yellow). The AUV navigation was poor due to the lack of LBL fixes and the drag associated with an attached safety tether.

The main focus for UAV operations during ICEX 16 was to determine an operating envelope for each specific platform. ICEX provides a unique and challenging environment for testing the UAV systems. In collaboration with Naval Special Warfare (NSW) a Scan Eagle was tested and Puma System. The Scan Eagle system provided a number of different challenges. The initial challenge faced was the logistics of transporting the equipment to the ice floe.

The other main challenges encountered were engine temperature and fuel lines. During the system check on the ice floe the engine performed as normal when the engine temperature was above 140 Celsius and RPM's were above idle. As soon as the RPM's dropped to idle and the engine temperature dropped below 140 Celsius the engine would shut off. The normal operating engine temperature is 120 Celsius and the maximum temperature is 180 Celsius. Currently there is no method for regulating the engine temperature. At -32 Celsius the fuel lines were hardening and shrinking because of the extreme cold. The shrinkage was causing the fuel lines to separate from the connection point to the engine, which was causing fuel to leak out of the aircraft.

NSW and NPS flew the Puma UAV and provided video to the command center of a Submarine surfacing on the ice. The Puma UAV operating flight envelope was successfully determined. The Puma flew in 25Kts winds and temperature of -32 Celsius. The only affect in flight performance was degradation in total flight time. The maximum flight time was decreased by 40 minutes. Fallow on research will address all of the challenges discussed above.

In summary, CAVR personnel successfully deployed the REMUS and SeaBotix (ACQUAS) AUVs during the ICEX16. Of the listed objectives 5 of the 6 were accomplished. The exception was navigating relative to the under-ice. This was not accomplished due to the unanticipated challenges associated with the REMUS AUV. ICEX16 provided a great venue for testing unmanned systems in an extreme cold weather environment.

Two NPS students, LT Pete Tydingco and ENS Eric Bermudez were brought along on the expedition. LT Tydingco's thesis was on Optimal Spatial Estimation that is fundamental towards estimating the under-ice topology with limited bathymetric sonar measurements. ENS Bermudez's thesis involved hydrodynamic modeling of the REMUS AUV and the control of the cross tunnel thrusters to maneuver the vehicle back to a docking station (or a moving ice hole). The experience provided a unique opportunity for thesis research relevant to naval mission objectives in a unique location.

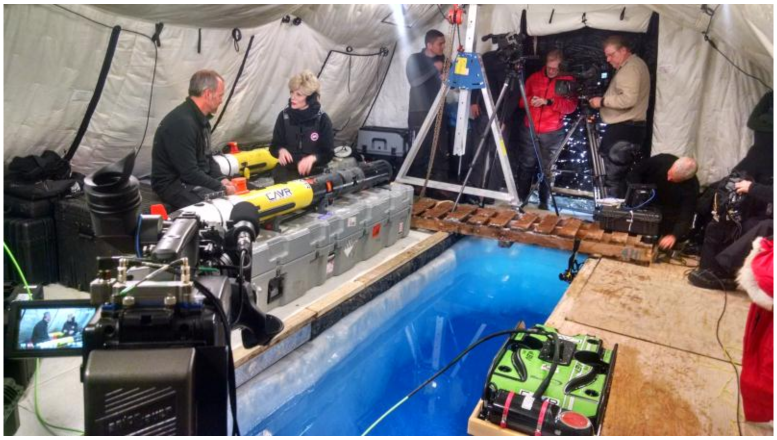


Figure 18. Dr. Douglas Horner interviewed for *60 Minutes* with Lesley Stahl.

Finally the CAVR team had the good fortune of being interviewed for a 60 Minutes news segment (*see Figure 18*). This was part of an overall segment on ICEX 2016 under the background of the strategic implications of the changing Arctic environment due to global warming.

POC: Dr. Douglas Horner (dphorner@nps.edu)

14. Short Range Wireless Power Transfer (WPT) for UAV/UAS Battery Charging – Phase III

The Phase III (FY16) work is a continuation of the previous two phases that investigated various methods of wireless power transmission (WPT) for UAV battery charging and propulsion. For ranges less than a couple of centimeters inductive WPT systems are viable. Inductive systems use two coils, one in the charging station and the second in the device. The energy is transferred by the magnetic fields linking the coils. At the receive coil, circuits are required to rectify and condition the output voltage for charging the battery. This approach was the primary focus of Phases I and II.

Radiative WPT systems use two antennas rather than coils, and the energy is transferred by a propagating wave. Typically the two antennas are in each other's far field. This study phase has concentrated on a new approach to array near field focusing that allows efficient power transmission for closely spaced arrays, as is the case when a UAV is parked. Two commercial computational electromagnetic codes were used to simulate the antennas with and without phase corrections. The two software packages were ANSYS Savant and CST Microwave Studio. The first is a high frequency approximation that runs quickly and does not demand large computational resources. The second is a rigorous solution that includes coupling between the antennas, but is computationally demanding (i.e., large amounts of RAM).

Two types of phase corrections were considered: (1) simple spherical wave and (2) conjugate phase matching. Simulations showed that the phase corrections can increase the efficiency dramatically, in some cases 10 dB (at 10 cm spacing for antennas operating at 3 GHz). It was found that the approximate simulation method is acceptable for distances that are slightly inside of the near field boundaries.

The details of the study are published in a MSEE thesis: "Phased Array Excitations for Efficient Near-field Wireless Power Transmission," by S. X. Hong (September 2016).

POC: Dr. David Jenn (jenn@nps.edu)

15. Low-Cost Expendable UAS with Application to Low Altitude Atmospheric Measurements

Small Unmanned Aerial Systems (sUAS) are a cost-effective and easy to use solution to fill a niche between surface-based measurement platforms (e.g. buoys, ships, WaveRider, etc.) and measurements with manned aircraft, providing a three dimensional view of the lower atmosphere. Small UAS are advantageous over other platforms such as ships or large buoys because they introduce minimal flow distortion or thermal heating to their environment. Their form factor lends itself to be deployed and utilized within physically constrained areas at altitudes where tower-based measurements are not possible. A specific application of sUAS is atmospheric sampling from the ocean surface up to 100 m to quantify evaporation ducts that affect the propagation of radar and communication signals. Lack of in situ measurements in the lowest 10-30 meters of the atmosphere with sufficient vertical resolution and statistical representation hinders development of improved surface layer models for quantifying evaporative ducts.

Our work on developing meteorological measurement capabilities with sUAS includes two parts as a joint multi-disciplinary effort between the Meteorology Department and Mechanical and Aerospace Engineering Department. One is airframe modifications and the other is meteorological sensor testing and validation. Several efforts have been made to improve flight characteristics of the airframe and allow for water landing. Wooden parts are replaced with 3-D printed andwater-safe composite materials that add strength and reduce weight. An improved modular motor mount was added to increase prop clearance with improved motor/ESC (electronic speed control) cooling and to make it easy to service/swap the motor and ESC. In addition, the modular avionics tray was redesigned and modified with printed bay lid, formed canopy, soft-mount for autopilot, and hard-points for payload. The improved motor mount, propeller, and streamlined canopy designs have improved the aerodynamics of the airframe, in turn providing increased flight endurance. A thermoformed plastic “bucket” was also made to help prevent water intrusion in the avionics bay during a water landing.

For sensor development, two sensor packages were tested for their profiling measurement capabilities during ascent and descent. Accurate refractivity profile measurements rely heavily on humidity, temperature, and pressure. The two sensor packages tested are manufactured by Intermet Systems. One is the iMet-XQ UAV sensor package designed for UAV applications and the other is an iMet-1-RSB rawinsonde repackaged and modified to fit onto the sUAS system. Test flights were conducted during the JIFX exercises at Camp Roberts this year. Data analyses suggest that both systems are comparable in sensing air temperature with fast response.

Unfortunately, relative humidity measurements from both sensors seem to be problematic. The iMet-XQ relative humidity appears to respond faster than that of the iMet-1-RSB rawinsonde, however it is noisy and introduces significant error for calculating water vapor content. The iMet-1-RSB rawinsonde RH sensor shows an overly smoothed variation and slow response time, which cannot provide adequate vertical profiles. The impact of this slow response needs to be further investigated and compared to other research-grade sensors. Lastly, a small bias of barometric pressure is also observed between the two sensor packages as the rawinsonde barometric pressure was inside the cabin.

Another part of the sensor development effort is to examine mean wind retrieval from the sUAS avionic system. Due to the lack of flow angle measurements (with respect to the airframe), various assumptions are made for wind retrieval and result in uncertainties in calculated wind measurements. Mean wind from four retrieval algorithms are compared. Further testing is needed with flights in auto pilot mode to provide better controlled flight patterns to aid in the wind retrieval. Future research efforts will attempt to develop affordable flow angle sensing capabilities, providing a proven solution to improve and characterize wind measurements from such aerial platforms.

POC: Dr. Kevin Jones (kdjones@nps.edu) and Dr. Qing Wang (qwang@nps.edu)

16. Glider Based Ambient Noise

The Tactical Oceanography course (OC4270) is a capstone course for both the USW and METOC curricula and is a class often taken by international students working on a master's degree in in Physical Oceanography. The course includes at-sea experimentation with a focus on studying the environmental effects on underwater acoustic propagation of signals and noise. With the assistance of previous CRUSER support, ocean glider operations have become a primary component of the at-sea field work to collect both ocean and acoustic measurements, as demonstrated at TECHCON-2015. Students analyze the field data to address tactically-relevant topics and present their findings at the end of the quarter.

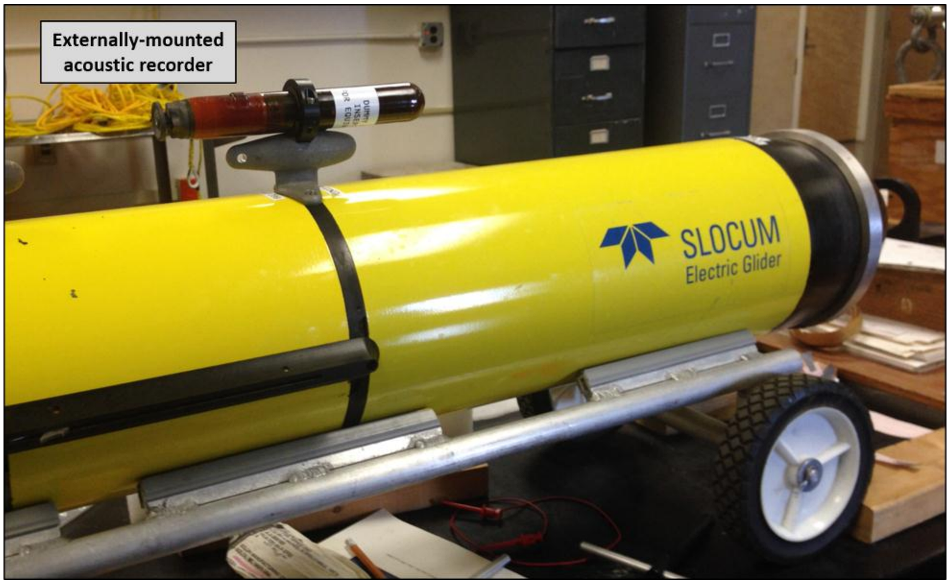


Figure 19. OC Slocum glider with externally mounted acoustic recorder

The current acoustic systems being used on the glider are self-contained ad-hoc systems that have proven to be useful, but have significant limitations. They are single-phone systems that are mounted inside the glider's science bay that exposes them to frequent internal sounds generated by the glider and are acoustically shielded by the glider's pressure hull, science bay enclosure and ballast system. This effort has developed an external mounting for an acoustic receiver for the Slocum glider (*see Figure 19*) which is expected to significantly improve acoustic reception by removing shielding effects of the glider's science bay. The way the Slocum glider conducts its missions with an acoustic sensor aboard has been modified by allowing it to go into a "drift mode" at depth for a specified time before returning to the surface. While the glider is in drift mode, internal self-noise generated by the glider's buoyancy control system and flow noise over the receiver caused by glider movement through the water are minimized. Acoustic reception is also improved in a downward refracting environment with the receiver deeper in the water column. Currents at depth are normally less than surface currents allowing the glider to remain on station in drift mode for longer periods, maximizing acoustic data recordings at optimal depths.

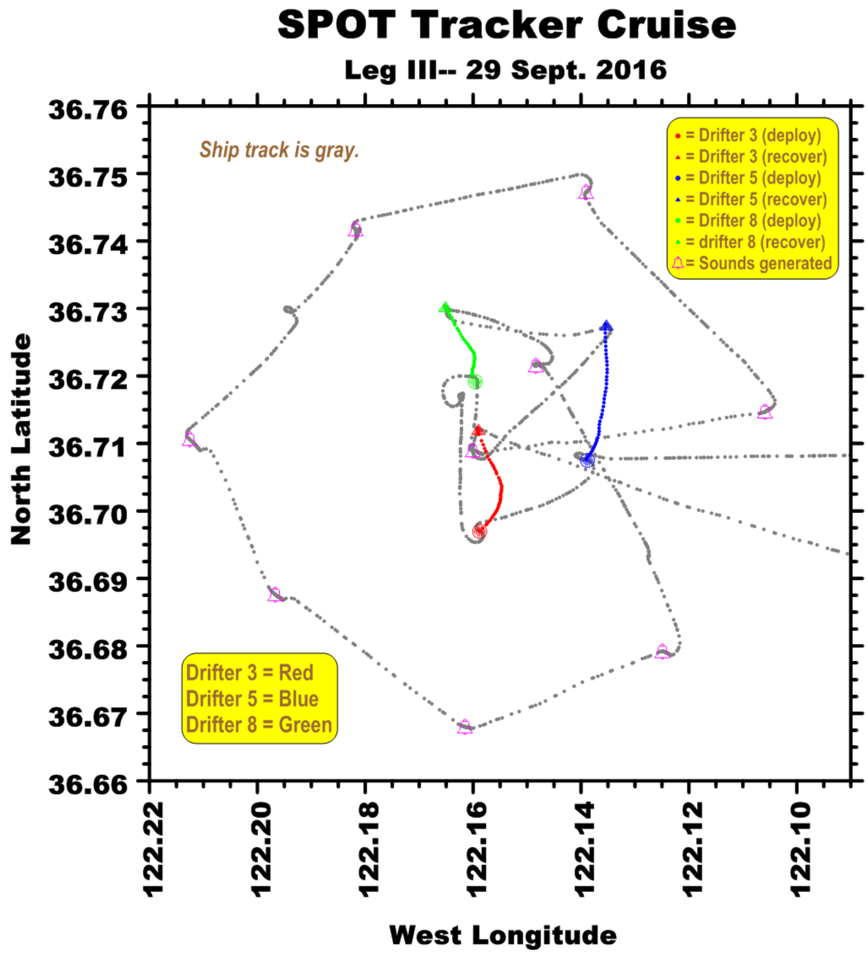


Figure 20. Acoustic data collection experiment on 29 September 2016. Signals from RV Fulmar were transmitted at various azimuths to multiple time-synchronized drifting receivers simulating gliders in drift mode.

Full testing of these improvements continues into FY17 due to delays in implementing a new user interface developed glider operations. As a surrogate for drifting gliders, multiple tracked drifting buoys with suspended acoustic recorders were deployed in Monterey Bay to collect acoustic data (fig 2), simulating multiple-glider operations that can provide multi-channel information for acoustic directionality and localization. The acoustic receivers were time-synchronized to allow use of "time difference of arrival" (TDOA) calculations to localize transient sounds. Signals transmitted from a research vessel at known locations provided ground-truth information to verify the accuracy and measure uncertainty associated with this method (fig 3). Once performance is established, localization of other sounds of opportunity (eg, marine mammal vocalizations) and directional ambient noise sources can be accurately determined from this data set. Analysis of this recently collected information is ongoing.

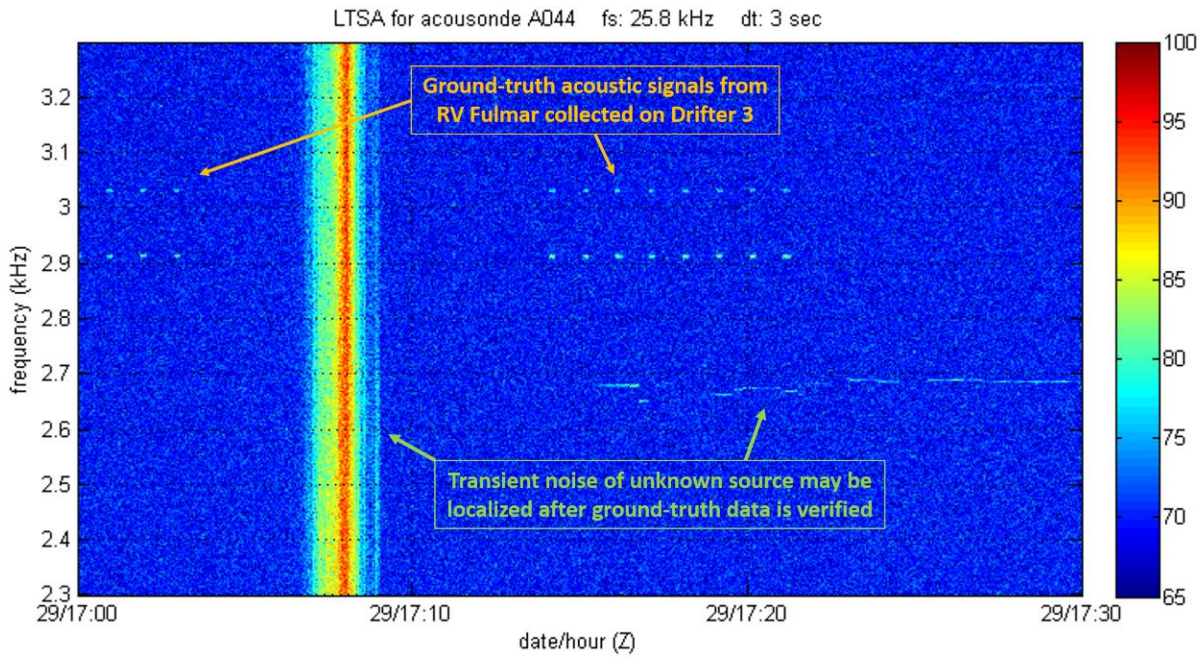


Figure 21. Snapshot of acoustic data collected shows reception of ground-truth signals transmitted from RV Fulmar and signals of opportunity that may be localized by receivers on drifting unmanned systems.

POC: Dr. John Joseph (jejoseph@nps.edu)

17. Optimal Intelligence Gathering and Defense Strategies against a Swarm Attack on a High Value Naval Unit

The goal of this project is to develop new optimal information gathering and defense strategies for the defense against an attack on a High Value Naval Unit (HVNU) by a swarm of Unmanned Surface Vehicles. Assuming that only probabilistic prior knowledge of the time and place of the attack and of the weapons carried by the swarm is available, the challenge in obtaining an optimal solution to this problem is to build an appropriate framework that explicitly addresses the underlying uncertainty.

Previous research resulted in the development of a computational and theoretical framework to generate optimal control solutions for use in scenarios, where underlying system uncertainty is the characteristic feature. These developments allow optimal utilization of all gathered information about the uncertain swarm system when creating tactical plans.

In the first part of this project focused on cost quantification in swarm defense situations with rapid-fire weapons activity between the defenders and the attacking swarm. The numerical resources mentioned above shed some of the simplifications of the combat models of the past, such as constant firing rates or stationary targets. This new framework is applicable to large swarms with nonlinear dynamics and can account for variable equipment capabilities, as well as equipment limitations such as range and point-of-view (POV) constraints

The second part of the project examines incorporation of attacking swarm uncertainty and the resulting optimization problems which arise when this uncertainty is paired with the new cost metrics developed in the first part.

Specific focus is on situations where swarm uncertainty is characterized by a set of constant but unknown parameters. This research shows that costs conditioned on this uncertainty fall into a class of optimal control problems where the constant but unknown parameter values are incorporated in the cost function and state dynamics.

POC: Dr. Isaac Kaminer (kaminer@nps.edu) and Dr. Claire Walton (

18. Sensor-Based Motion Planning for Marsupial MCM Teams

This research project is motivated by recent efforts at the Office of Naval Research to develop a marsupial system-of-systems to conduct all three phases of mine countermeasures (MCM) operations in a single sortie: 1) detection/classification, 2) reacquisition/identification, and 3) neutralization. This system will be comprised of an unmanned surface vessel (USV) which can autonomously transport, deploy, recover, and sustain multiple types of Autonomous Underwater Vehicles (AUVs) to conduct each phase in sequence. The working hypothesis is that significant cost, complexity, and time savings might be realizable if the USV in this system could also provide fast, wide-area mine detection in phase 1, obviating the need to carry multiple large AUVs dedicated to this purpose. Under this CONOPS, phase 1 and phase 2 could be conducted in tandem, with the USV deploying AUVs as needed to reacquire and identify targets detected by its sonar. The USV could also provide updated targeting info and navigational guidance to reacquisition and neutralizer AUVs via an acoustic modem. The focus of this research was to develop algorithms and communications software for eventual experimentation using vehicles at the Naval Postgraduate School (NPS) Center for Autonomous Vehicle Research (CAVR). Previous research efforts resulted in the integration of a sophisticated forward-looking sonar (FLS) onto a SeaFox USV, and CAVR routinely deploys multiple REMUS 100 AUVs equipped with high resolution sidescan sonar (SSS) which are representative of vehicles used during phase 2 of MCM operations.

Our technical approach utilizes an optimal control framework for motion planning. This framework combines key elements from search theory with recent theoretical and computational results developed jointly at NPS and the University of California at Santa Cruz. It allows the numeric solution of "generalized" optimal control problems that explicitly account for vehicle dynamics, sensor performance, and uncertain target locations. This year, the research team developed physics-based sonar detection models for different mine-hunting sonars used by the Navy and at CAVR. Examples include the Autonomous Topographic Large Area Survey (ATLAS) FLS, BlueView 450 kHz and 900 kHz imaging sonars, and a Marine Sonics SSS utilized on REMUS 100 AUVs. Also developed were kinematic models for various unmanned surface and underwater vehicle platforms. Lastly, optimization functions based on each sonar's probability of detecting mines from a moving vehicle in a notional environment were developed. This benchmark problem served as a baseline for comparing the mission performance of different autonomous vehicle teams. Using the NPS High Performance Computing cluster, a large number of Monte Carlo simulations were conducted to identify the influence on search performance of different sonar design parameters and team compositions in a time-limited MCM operation. This analysis suggests that the computational framework, in addition to generating feasible vehicle trajectories for optimal search, can also inform mission planners on the optimal suite of vehicles and sensors to employ for a given mission. Continued development of this capability into a useful mission planning tool for MCM in FY17 has been proposed.

Experimental work this year focused on the acoustic modem software required for inter-vehicle communications within the MCM team. CAVR has designed a software architecture based on the Robotic Operating System (ROS) that runs on all of its unmanned vehicles, including the SeaFox USV, the REMUS 100 AUVs and the Agile Close-Quarters Underwater Autonomous System (ACQUAS). This year, CAVR developed an acoustic communications (ACOMMS) software module that utilizes Micromodems from the Woods Hole Oceanographic Institution (WHOI) to perform multiple functions: 1) sending data from one vehicle to another, 2) measuring the range between vehicles, and 3) fixing a vehicle's position relative to a pair of REMUS navigational transponders. These functions will allow the USV to provide tasking and navigational updates to team members during an MCM mission. In FY16, CAVR tested these capabilities on the REMUS and ACQUAS vehicles during the ICEX '16 and NASA Extreme Environment Mission Operations (NEEMO) field experiments. At NEEMO, the ACQUAS successfully sent an acoustic modem command to launch a REMUS vehicle from its starting location. Encouraged by these results, CAVR will continue developing this architecture toward robust collaboration by heterogeneous vehicle teams.

POC: Professor Sean Kragelund (spkragel@nps.edu)

19. Non-RF Communications for Scan Eagle Unmanned Aerial Vehicle

US Navy has an emerging requirement for alternate means of communicating with the Scan Eagle Unmanned Aerial Vehicle (UAV). The use of Radio Frequencies (RF) is the only method for communicating with the Scan Eagle. There are two communication links, one for command and control and the other as a video down-link. The Frequency for each is 1.3Ghz and 2.4Ghz respectively. The Scan Eagles use of RF makes it susceptible to jamming. The US Navy depends on RF for employing command and control of tactical forces. Since the Navy uses RF for communications, an adversary would have interest in those communications. The interest is in two main areas: (1) interception of the information over the communication channel, and (2) denying the sender and receiver to successfully exchange information. The focus is on the second of the two areas. Jamming approximately 30 % or more of a voice transmission will degrade the intelligibility significantly such that it will deny an effective transfer of information. Noise jamming is a technique used for jamming. In which the jamming carrier modulates a random noise waveform. The purpose is to disturb the communication waveform by inserting noise into the receiver. The bandwidth signal can be as narrow as only occupying a single channel or as wide as the entire spectrum width. Effects can vary depending on the details of the implementation An approach to dealing with jamming is through the use of FSO. Free Space Optics use optical wireless units to establish connectivity, each unit consist of an optical transceiver with a transmitter and a receiver to provide full-duplex capability. An optical wireless unit uses a lens to receive information from another unit, which uses an optical source and lens to transmit light through the atmosphere. This research proposes the development of alternate means of communication for the Scan Eagle UAV, using Free Space Optics. Specific objectives include identifying a free space optics sensor that meets the Scan Eagle's size and power constraints. Furthermore, integrate and test the identified free space optics sensor.

This year's work was focused on identifying a manufacturer of a FSO system. The search produced two companies, Boston Micromachines and SA Photonics. A cubesat system from both companies have been identified, both of which are prototypes. The Boston Micromachines system has a throughput of 700Kbps, while the SA Photonics has a throughput of 125Mbps. The distance for both systems were comparable. SA Phontonics was chosen as the company with the ideal system for Scan Eagle. This determination was made during the technology review of both companies. Determining factors were technology maturity and overall performance. The SA Photonics system provides up to 50 degrees of beam steering for target acquisition and has a peak power consumption of less than 15W. The physical dimensions for the system are 4" x 4" x 3.5" and weighs 1.5Lbs. Due to the nature of this system being a prototype, the team was unable to perform a field test. An additional system was identified with similar capabilities that could be field tested as a surrogate. The system that was chosen was the Nexus 3 FSO system. The Joint Interagency Field Experimentation (JIFX) in August 2016 was chosen as the venue for field experimentation. The Nexus 3 was tested at three different link distances: Day 1- 2.9km, Day 2- 7.4km and Day 3- 9.4km. During the entire test evolution a throughput of 9 Gbps or greater with Autonomous acquisition and reacquisition was maintained. The field testing of the Nexus 3 allowed validation of the FSO technology as a viable solution for replacing the traditional RF Communications Link for Scan Eagle. Additional development and testing of the cubesat must be performed before research can proceed with integration on board a Scan Eagle. Follow on work will allow for integration and possible flight testing of the entire cubesat system on board a Scan Eagle.

POC: Professor Aurelio Monarrez (amonarre@nps.edu)

20. Command & Control for Teams of Autonomous Systems and People

The objective of this research is to address command and control (C2) for teams of autonomous systems and people (TASP), especially within the context of next generation unmanned aircraft systems (UAS), and to employ computational experimentation to lay out a path for overcoming critical C2 issues.

This stream of research seeks to stay five to ten years ahead of practice, which enables us to anticipate both issues and opportunities in an area that remains under researched: C2 of autonomous systems (esp. unmanned vehicles, robots, Cyber applications). In great contrast with the huge effort expended to investigate the technologic characteristics, developments and advances of autonomous systems, a dearth of research addresses the corresponding C2. This is despite the quintessential importance of C2 and the fact that current C2 strains under the load of having even two UAS, for instance, flying simultaneously in common airspace. Exacerbate such load with large numbers (e.g., swarms) of UAS, then exacerbate further with missions that integrate manned and unmanned aircraft, and one realizes quickly that contemporary C2 organizations and approaches are likely to fail in just a few years.

Yet swarms are on the horizon now, as are many integrated manned-unmanned missions that can outperform those of either manned or unmanned alone. Indeed, an adversary with C2 capable of handling TASP missions can gain competitive advantage, even with autonomous systems that are technically inferior.

Using computational experimentation, the team investigated a systematic array of UAS technologies and levels of manned-unmanned mission integration, assessing the comparative mission performance of alternate C2 organizations and approaches across multiple metrics (e.g., mission duration, errors, delays, rework, cost and risk; C2 coordination & communication load), which provide insights into why C2 breaks down and how to overcome its critical issues. Such insights enable us to anticipate key milestones in terms of C2 failure, and to lay out in advance the actions required to obviate such failure, as a road map for Fleet implementation.

Building upon leading edge research to understand the properties and behaviors of next generation unmanned aircraft systems, recently enabled C2 computational modeling and simulation capability to integrate the corresponding UAS capabilities has been expanded. This affects in particular two degrees of autonomy (D4 & D5) across all levels of manned-unmanned mission integration. Hence roughly 40% of computational models have changed as a result of this research update, and preliminary results suggest a more nuanced perspective of TASP C2, on which offers good potential to inform current organization leaders and policy makers, in addition to laying out a migration path for future leaders and operators. For instance, findings show how a transition to reciprocal and especially mixed interdependence (esp. integrated manned-unmanned missions) represents a discontinuity and signals an abrupt increase in mission risk to unacceptable levels.

The project is ongoing at the time of this report, with the simulation work nearly complete and the analysis and technical reporting efforts scheduled for completion in November.

POC: Professor Mark Nissen (MNissen@nps.edu)

21. Using Small Unmanned Aerial Systems as Electronic Warfare Platforms - Providing the Tactical Ground Commander the Electromagnetic Advantage

Direction finding (DF) systems are fundamental electronic support measures for electronic warfare. A number of DF techniques have been developed over the years; however, these systems are limited in bandwidth and resolution, and suffer from a complex design for frequency down-conversion. Advancements in digital signal processing and solid-state technologies have led to the proliferation of low probability of intercept (LPI) radars. This class of radar transmits special waveform types with the objective of preventing detection or tracking by non-cooperative intercept receivers [1]. When guided missiles or anti-radiation missiles are equipped with LPI radars, they become a formidable threat to ground-based, airborne, or shipboard radars as the missiles can home in on their target without themselves being detected. To this end, much attention has been placed on developing new and effective techniques to detect threats emitting LPI signals and to estimate their angle of arrival (AOA).

This research builds on the earlier research for a microwave-photonic direction finding system [2, 3]. Major enhancements were made to simplify the RF frontend design, and to improve the system sensitivity. A simulation model was built to help verify the system response to LPI signals, and a unique encoding method was used to resolve the AOA ambiguities over the entire field of view with high accuracies. The LPI signals analyzed included linear FMCW and P4-coded waveforms at a carrier frequency of 2.4GHz. Experimental test conducted in the anechoic chamber showed that the system was able estimate the AOA of linear FMCW at 1° resolution with an RMS error of 0.29° and P4-coded signal at 1° resolution with an RMS error of 0.32°.

Key advantages of this design include a small baseline, wide bandwidth, high resolution, minimal space, weight, and power requirement thus raising the possibility of deploying such capabilities on small unmanned aerial systems such that the Tactical Ground Commander may be able to take the initiative in the electromagnetic battlespace.

PROJECT REFERENCES

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POC: Dr. Philip Pace (pepace@nps.edu)

22. Stratified wakes induced by submerged propagating objects: detection using USVs and UUVs

During the current period of performance, this research group made several major advances in the analysis of stratified wakes. This study used a combination of numerical simulations, analysis of field data, and laboratory experiments to identify measurable hydrodynamic signatures induced by a moving object in the stratified ocean with the ultimate goal of prediction for dependence on the speed, size, and motion pattern of a submersible. The key accomplishments include the analysis of three data sets generated from super computer numerical experiments conducted using the Massachusetts Institute of Technology General Circulation Model (MITgcm) to simulate the stratified wake observed in field experimentation with a towed body in Monterey Bay, CA. Horizontal and vertical model domain cross-sections were examined to determine wake magnitude and development. The "synthetic REMUS" simulations were used to analyze thermal measurements across the modeled wake for validation of field data. Analogous data processing algorithms were applied to both the real-world and model environment temperature data for resolution of turbulence characteristics. This research found that both the field REMUS and the synthetic REMUS were able to detect stratified wakes by identifying ~0.1 deg C spikes in root-mean-square (RMS) temperature perturbations. The findings also confirmed (Moody, 2016) that the tow vessel had a negligible effect on thermal turbulence characteristics for 10-20m depths. A 0.9m diameter submerged object propagating at 6 knots will generate roughly a 10m spherical wake within two minutes given similar stratified environmental conditions. The wake signature could be measured through turbulent characteristics on time scales exceeding 45 minutes, which was the full programmed REMUS mission time used for data collection.

The modeled numerical simulations are consistent with the field work and that thermal wake detection is possible by measuring turbulence characteristics with an AUV. Faster towed body velocities produce larger wakes, both in the vertical and horizontal expansions. This suggests that a larger and faster submerged propagating body will produce more detectable wakes with even greater residence times. There is a strong relationship between intensity of the wake, the stratification of the fluid, and the velocity, diameter and depth of the propagating object. LT Zachary Moody methodically examined thermal variations caused by stratified wake turbulence and reported his findings in his NPS thesis (Moody, 2016).

The project has involved six NPS students. LCDR Merriam has successfully completed his MS thesis entitled "Laboratory experiments on stratified wakes" (Dec. 2015). LT Benbow has successfully completed his MS thesis entitled "The effects of double-diffusion and background turbulence on the persistence of submarine wakes" (Mar. 2016). LT Moody has successfully completed his MS thesis entitled "Stratified wakes induced by submerged propagating objects: detection using UUVs" (June 2016). LT Martin has successfully completed his MS thesis entitled "Influence of the momentum excess on the pattern and dynamics of stratified wakes" (June 2016). LT Danner and LT Lorfeld will be continuing the research into non-acoustic detection for their thesis project by incorporating a USV wave glider and thermistor string to develop cross-section measurements for a stratified wake generated by a towed body in the Monterey Bay.

POC: Dr. Timour Radko (tradko@nps.edu)

23. Characterization of the Arctic acoustic environment using unmanned mobile sources in ICEX-16

Recent changes in the Arctic environment mean that operational databases are becoming more uncertain and operational TDAs can be expected to perform ineffectively in the "new" Arctic due to poor environmental input and lack of understanding of the acoustic phenomena, leading to improper placement of assets and potential exposure to shorter than expected counter-detection ranges. Understanding this new environment and the physical processes at work will identify acoustically-relevant environmental factors which are critical to successful future deployment of naval assets in the Arctic. This effort is synergistic with other ICEX scientists collecting environmental data and conducting large- and small-scale ocean and ice modeling to complement the data collection while offering students thesis research opportunities to address the challenges of Navy operations addressed in the CNO's Arctic Roadmap 2014-2030.

Our primary objective was to use unmanned mobile sources (aka, EMATTs) and other sensors in this ice-covered environment to collect 3D (depth, range, azimuth) acoustic propagation information that would not otherwise be feasibly attained with either manned or fixed assets. Students are using these data with ancillary oceanographic information to investigate issues that have direct impact on acoustic propagation characteristics including changes in (1) under-ice thermohaline structure, (2) under-ice roughness of first-year ice versus multi-year ice, (3) ice content and structure and (4) ice zone ocean dynamics.

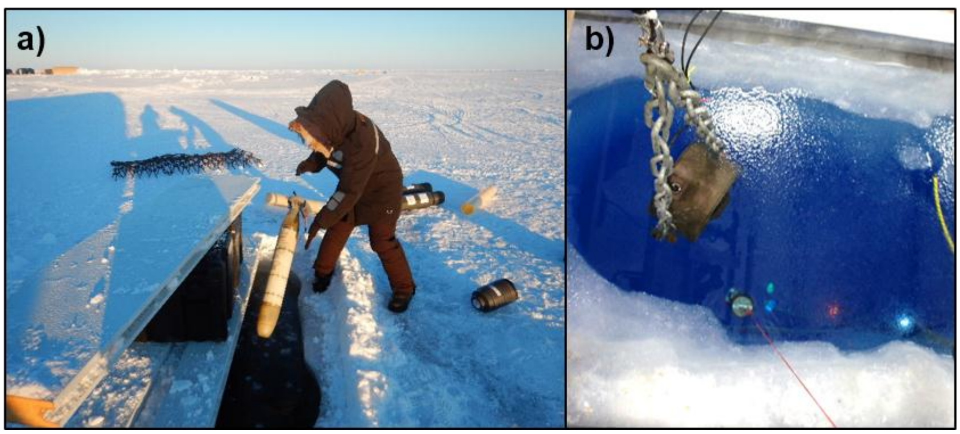


Figure 22. a) LT Kristine Bench deploys an unmanned mobile acoustic source through the ice at the diver escape hole near Camp SARGO (in background). b) A mid-frequency transducer (on chain) is lowered through the ice for transmitting signals at various depths to 700m.

Three NPS students and one faculty were deployed to Ice Camp SARGO from 08-13 March for the early part of the exercise as camp facilities were still being set up. Acoustic signals were transmitted from four unmanned mobile acoustic sources (fig 1a) to provide 3D propagation information, and from a mid-frequency transducer suspended under the ice (fig 1b) at the ice camp to provide data along specified acoustic paths. Transmitted signals and ambient noise were collected by two vertical line receiving arrays (VLAs) located 1-3 km from the camp (fig 2) over a 5-day period. In conjunction with the acoustic data, multiple CTD (conductivity, temperature and depth) profiles to 500m depth were collected at the ice camp and a time series of CTD information at specified depths was collected at the two VLAs.

Figure 23. A vertical line array (VLA) with sensors down to 400m is set up several kilometers from Camp SARGO to receive signals transmitted by both mobile acoustic sources and the mid-frequency transducer at the ice camp. L-R are LT Mitch Nelson (USW student), LT Kristine Bench (METOC student), LCDR Dominic DiMaggio (OC PhD candidate) and John Joseph (OC Research Faculty).

Our data collection objectives were fully met during ICEX-16 and the information is currently being analyzed. All indications are the four mobile sources performed as planned, each providing a very rich data set (fig 3) during their 8+ hours of acoustic broadcasts at various depths. ICEX-16 data were the basis for a master's thesis authored by LT Mitch Nelson, a September 2016 NPS graduate of the Undersea Warfare curriculum. His investigation has uncovered some very significant acoustical impacts on short-range propagation caused by a highly turbulent layer in the upper water column (50m depth). Other students are continuing the analysis of this unique data set.

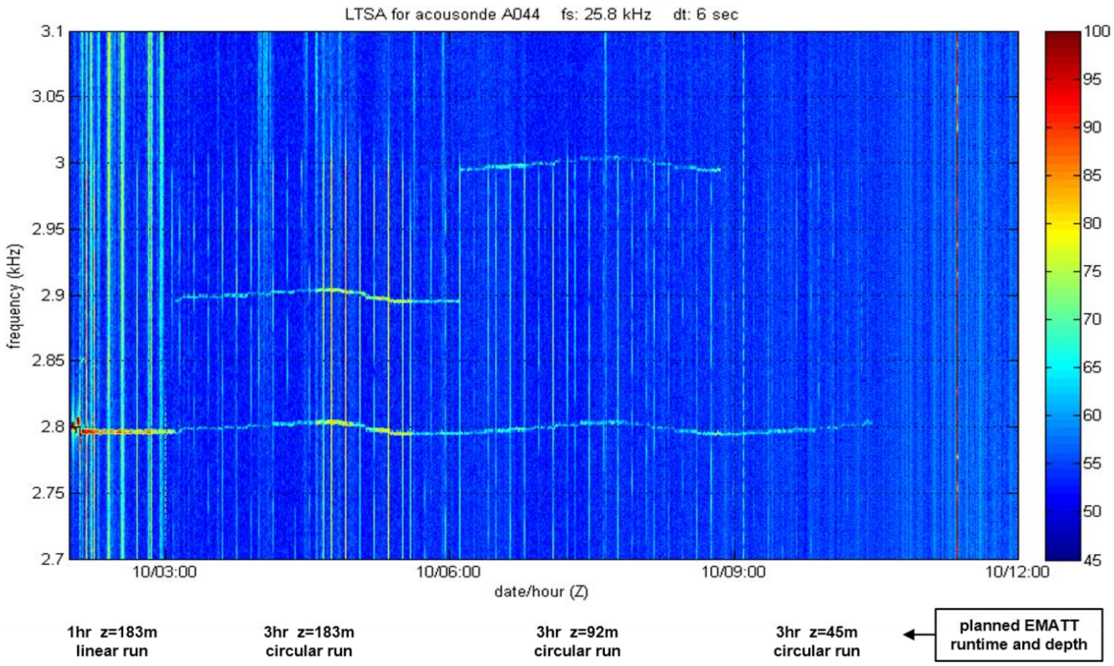


Figure 24. A spectrogram of the acoustic data shows signals from an unmanned mobile source were continuously received over the entire planned mission time (>8 hours) providing 3D information not otherwise feasibly attained from either manned or fixed assets.

Unmanned mobile sources were used as a very effective research tool in ICEX-16 and will pioneer the way for the use of other more sophisticated mobile sources such as the recently developed and delivered REMUS-100 mobile source that can carry complementary environmental sensor packages to collect data in extreme environments. CRUSER support for these activities is greatly appreciated.

POC: Dr. B. Reeder and Dr. J. Joseph (jejoseph@nps.edu)

24. Project Manicopter: Autonomous Aerial Vehicles with Robotic Manipulation Capability

The availability of an autonomously operated manipulator gives UAVs the unique capability of physically interacting with the environment and/or with other objects and vehicles. This capability enables UAVs to conduct new critical missions such as transportation of ground robots, landmine detection/removal, and defensive countermeasure, picking/assembly, data acquisition/inspection of vertical surfaces of ships, etc. This project investigated the dynamics, guidance, and control of autonomous air vehicles with robotic manipulation capability for the physical interaction with other objects. Toward this goal, guidance and control algorithms for real-time path-planning have been developed for missions using a hexacopter to contact with the environment. A force and torque control method has also been developed to enable interaction with the environment and to response against collision detection. Development of robust adaptive control and model predictive control algorithms is in progress. The executive summary is as follows.

Development of a two-layer controller for translational motion of the hexacopter

- Two layer-controller has been developed and experimentally tested
- Translational motion and attitude stabilization control of the hexacopter were developed
- PID controller for translational motion was developed and validated via autonomous flight tests

Development of a robust control algorithm using L1 adaptive control method for precise hovering

- L1 attitude controller has been developed and simulated on the MATLAB/Simulink environment.
- Precise hovering and path tracking has been achieved in simulations
- Experiments to validate the L1 attitude controller are in progress

Development of model predictive control (MPC) for obstacle avoidance

- MPC approaches to avoid multiple obstacles have been developed
- Simulation and experimentation work are in progress to apply to multicopters

Development of a contact and collision detection algorithm

- A force estimation algorithm to detect collision and contact has been developed
- Experimental validation of the algorithm has been implemented using a small quadcopter

Future work

- Experimentation of guidance and control algorithms for the manipulator
- Development of multicopter force and torque control algorithms
- Experimentation on preliminary test mission scenarios in the lab, such as picking objects, pushing buttons on a vertical surface, rotating handles, and door/drawer opening, etc

Publication

[1] E. Capello, H. Park, B. Tavora, G. Guglieri, and M. Romano, 'Multicopter identification approach via a compound pendulum test rig,' Journal of Guidance, Control, and Dynamics, under review.

[2] E. Capello, H. Park, B. Tavora, G. Guglieri, and M. Romano, 'Modeling and experimental parameter identification of multicopter via a compound pendulum test rig,' International Workshop on Research, Education, and Development on Unmanned Aerial Systems (RED-UAS), Cancun, Mexico, November, 2015.

POC: Dr. Marcello Romano (mromano@nps.edu)

25. Data Farming Short Course Development for the CRUSER Community

NPS's Simulation Experiments & Efficient Designs (SEED) Center for Data Farming is internationally recognized for its advancement of both the theory and the practice of large-scale simulation experiments. Many SEED Center students have already applied design of experiments (DOE) techniques on agent-based or discrete-event simulation models to explore scenarios involving unmanned vehicles in operational environments, with great success. The students have come from the Army, Navy, Marines, and Air Force, as well as international allies. They have investigated unmanned vehicles of many types—aerial, ground, surface, and underwater—for missions related to reconnaissance and surveillance, IED detection, mine detection, border security, asset protection, casualty evacuation, humanitarian logistics, and more.

To share these methods with the larger community, SEED faculty developed tutorial materials, including slides and simulation software examples. A set of data farming scripts that are useful for running designed simulation experiments in batch mode was updated. These publicly available scripts are now fully self-documenting for ease of use. They are available for use in future workshops or short courses.

The team hosted three high school interns as part of ONR's Science & Engineering Apprenticeship Program (SEAP). They developed variants of epidemic models, with application to the spread of computer viruses on a network, the transmission of genetic diseases through a population, and the effectiveness of different interventions for wildfire control. These interns went through the tutorial materials and used a subset of the data farming scripts to conduct their experiments and analyze the results.

The team also delivered a half day tutorial on data farming at the OCEANS '16 Conference in Monterey, so that CRUSER researchers and other attendees who use simulation models to explore the potential utility of unmanned systems can get much more information about the effective employment and desired capabilities of those systems. This conference had many presentations on robotics and unmanned systems that are of interest to the CRUSER community. An example in this short course relates to the use of unmanned vehicles for naval operations.

Materials from the short course offering are available and available for other audiences should there be interest from the larger CRUSER community. Ultimately, a data farming approach will facilitate robust operational insights by assessing a broad range of "what if?" questions, rather than evaluating the performance of unmanned autonomous systems within a narrow, limited set of scenarios.

POC: Dr. Susan Sanchez (ssanchez@nps.edu)

26. Closing Capability Gaps: Data Farming Methods for New Concept Exploration in the CRUSER Community

Computer experimentation is integral to modern scientific research, national defense, and in public policy debates. These computer models tend to be extremely complex, with thousands of factors and many sources of uncertainty. Data farming helps researchers understand the impact of those factors and their intricate interactions on model outcomes. Data farming is the process of using carefully chosen computational experiments to grow data, which can then be analyzed using statistics and visualization techniques to obtain insight. NPS's Simulation Experiments & Efficient Designs (SEED) Center for Data Farming is internationally recognized for its advancement of both the theory and the practice of large-scale simulation experiments.

During FY16, the SEED Center worked with many students who explicitly investigated the employment of unmanned vehicles in their research. Villatoro (2016) conducted classified research that explored the use of high energy lasers to defend against complex threat environments, including unmanned aerial vehicles. Sikander (2016) investigated ship-based UAVs and other combat capabilities in anti-air warfare environments, as part of a ship design process. Williams (2016) assessed the benefits of using the Coyote UAV to add a magnetic anomaly detection (MAD) capability to the P8-A for anti-submarine warfare, using several different CONOPS. Cheang (2016) considered defensive USVs and the Fire Scout unmanned autonomous helicopter as potential capabilities while developing an operationally-effective, operational energy-effective, and cost-effective capability portfolio for protecting a maritime force against small boat swarms. Schambach (2016) explored unmanned undersea strike weapons, and participated in CRUSER's Warfare Innovation Workshop. Three other students have work in process, ranging from modeling extended, long-range testing for UUVs in environments where tests may need to be interrupted (and later restarted) if marine mammals or other vessels are in the vicinity, to capturing the effect of degraded communications on ground combat operations with a mix of assets including both manned and unmanned aircraft.

In addition to these new concept explorations, this research project continued to advance the methodology, including the two papers listed below and ongoing work on adaptive sequential designs. These advances can be leveraged in future simulation studies.

POC: Dr. Susan Sanchez (ssanchez@nps.edu)

27. Robotics System Software Engineering Case study

The design, implementation, test and integration of hardware, software, people, and other system components has been and will continue to be the central technical activity in the creation and fielding of new defense capabilities. The use of a hands-on, end-to-end, robotic system example is an important enabler to NPS student learning. The purpose of this educational development project is to build a set of integrated material to provide that robotic system example. During FY 2016, the PI (Dr. Shebalin) and another NPS SE faculty member (Dr. Kristin Giammarco) have developed new material and modified existing material to create an example called the Tactical

Disk Clearance System (TDCS). The TDCS has as one of its components the Tactical Disk Detection System (TDDS) which is a working, hands-on robot (*see Figure 25*). The application of the TDDS robot to the classroom is flexible. A standard robot design can be used by an instructor to demonstrate various systems engineering lesson points to the students, or the instructor can have the students (typically in teams) analyze, design, implement and test their own robot designs, using LEGO Mindstorms NXT or EV3 robotics kits, based on TDCS and TDDS requirements. The basic LEGO Minstorms EV3 kit provides over 600 parts for robot design and there are several options for developing software. Discussed below are the FY 2016 accomplishments for this CRUSER educational development project.

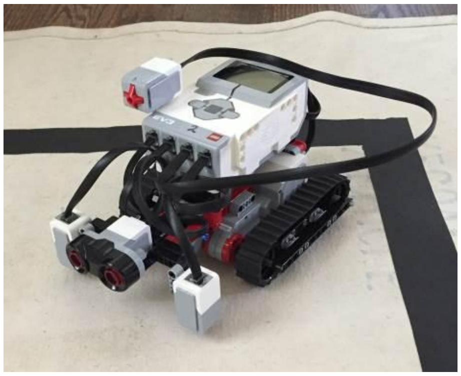


Figure 25. Standard Tactical Disk Detection System (TDDS) robot used in the SE4003 Systems Software Engineering course.

c. Defining and Testing the Radiological Container Clearance System (RCCS) Hands-On Robotics Challenge:

A Radiological Container Clearance System (RCCS) hands-on design project, using the EV3 version of LEGO Mindstorms, was completed by a five-student capstone project team advised by the PI. This RCCS project mimicked the DoD requirements definition and acquisition processes and created a robotic system that simulated clearing hazardous containers (plastic medicine bottles) from a four-foot by four-foot area. Prior to the students completing this challenge project, the PI created and tested his own prototype RCCS (see YouTube video, https://www.youtube.com/watch?v=aKShIZ4SzFU). Additionally, the PI developed systems engineering artifacts such as the functional flow block diagram (FFBD) and the sequence diagram. The results of this design project were working prototype robots (the PI's robot and the students' robot), systems engineering diagrams and descriptions, and a familiarity with the LEGO Mindstorms EV3 technology. It turned out that the RCCS autonomous container removal requirement was much more difficult for students to meet than the autonomous TDCS tactical disk detection requirement. The TDCS Challenge is discussed next.

d. *Standardizing the Tactical Disk Clearance System (TDCS) Hands-On Robotics Challenge:*

Systems engineering students experienced the design and development of the TDCS in two courses during FY 2016. First, as a hands-on team project in SE3100 Fundamentals of Systems Engineering in the Fall quarter and second, as an ongoing case study during SE4003: Systems Software Engineering in the Summer quarter. In SE3100, the PI had student teams of three use LEGO Mindstorms NXT kits to design and develop TDDS robots, including creating the software. In SE4003, Dr. Giammarco integrated the TDCS case into the weekly class sessions and used the TDCS as the basis for weekly assignments. Dr. Giammarco and the PI worked together to use the LEGO Mindstorms EV3 kits to create a standard TDCS/TDDS design (*see Figure 25*) and supporting documentation. A standard TDCS design reference mission (DRM) was baselined in a draft NPS Technical Report. Dr. Giammarco and the PI have made the standard DRM and the SE3100/SE4003 course material available for use by all SE faculty. Examples of this material are the state transition diagram and the FFBD.

e. *Future work*

As a follow-on to the FY 2016 project, there are three main efforts: build on and improve the existing material, integrate the material into other SE courses, and establish a process for making other faculty more comfortable with the material.

POC: Dr. Paul Shebalin (pshebali@nps.edu)

28. Real-time undersea networking using acoustic communications for improved UUV positioning and collaboration

The objective of this work was to successfully develop methods for the enhancement of the navigational and positioning accuracy of autonomous underwater vehicles through a combination of autonomous surface vehicles deploying underwater acoustic communications protocols. The majority of the data collection events supporting this effort were conducted in FY15.

Significant progress was made on the data analysis and tracking models in FY16. The team had also intended to collect additional data in FY16 with new acoustic modem hardware, which was procured and integrated on the two Wave Glider towfish systems in the lab. However, severe budgetary and procedural issues developed and funds were not secured until well into FY16. This precluded collecting additional data for analysis. A single sea-test was conducted at the very end of FY16, but did not produce any useful data. This data collection event will be attempted again in January 2017 under support from a different project. Therefore, the focus of FY16 efforts was on the data analysis and tracking model.

Acoustic modems are able to accurately measure the acoustic travel time from modem to modem. For this project, this information was used to make a rough estimate of the distance by multiplying the measured travel time by the characteristic medium sound speed. With the help of a ray tracing algorithm to model the acoustic channel, the ideal complex impulse response associated with the different multipath arrivals (eigenrays) was then used to construct the synthetic received signal. This signal was then cross correlated with a replica of the transmitted signal, producing a prediction of the channel impulse response.

The predicted channel impulse response was then used iteratively (adjusting the horizontal range in the ray tracing code) to match the measured channel impulse response with one caveat: instead of trying to match the entire time series, only the arrival with the highest amplitude will be matched in time. This procedure is fast enough to run on dedicated hardware in real time and, ultimately, can return a more accurate distance between source and receiver (both equipped with acoustic modems).

After determination of the distance between the source (located on the UUV) and multiple receivers at known GPS coordinates (located on the USVs), each obtained at different times, two tracking algorithms based on Kalman filtering (EKF and UKF) were employed to estimate the UUV position. These algorithm were first tested with synthetic data and validated using the data collected during sea tests in Monterey Bay in August, 2015.

During the sea tests, several one-hour missions were successfully conducted. For each mission, the UUV navigation system recorded its position predictions and, because of its simplicity, errors of the order of 500 meters and above were observed between the final UUV predicted position and its GPS location, measured soon after it surfaced.

Using the tracking algorithm, when a rough estimate for the distance between UUV and the USVs was used (multiplication of the one-way travel time by the characteristic medium sound speed), errors around 35 meters were observed at the end of the UUV's mission. While this was an improvement, it did not account for the multipath effects of the propagation.

When the more complete algorithm described in this work was utilized, the final error was reduced to around 15 meters for the EKF and 8 meters for the UKF based algorithm. Thus, the impact of correlating the measured impulse response of the channel with a ray trace prediction was confirmed, and provides an improvement in the tracking accuracy.

POC: Dr. Kevin B. Smith (kbsmith@nps.edu)

29. Enabling Secure Group Communications for UAV Swarms using Distributed Key Management

The advances made in swarm communications research both at NPS and at other institutions has exposed a major gap: the lack of basic communications security. This stems from various factors, including cost and how UAV performance is affected by computationally expensive data encryption and authentication computations. In the last several years, researchers have studied the various cyber security threats that UAV swarms face. These threats have been identified, along with extensive risk assessments. While there is a consensus in the research community that UAV swarms are vulnerable to cyber security attacks, there has been little movement in identifying appropriate algorithms to facilitate a security architecture for UAV swarm communications. Communications security is required between individual UAVs and between a UAV and the ground control station. This research project focused on the implementation of security algorithms for UAV to UAV data transfer and the impact of communication security on the swarm. This includes both encryption and authentication. Authenticated encryption (AE) is designed to simultaneously protect both a message's privacy and authenticity. The NPS ARSENL Lab UAV swarm was model on which various encryption and authentication algorithms were implemented and tested. For classified information communications, the Advanced Encryption Standard (AES) was studied. AES has been approved and adopted by the National Security Agency (NSA) as the official cryptographic module for the transmission of SECRET and TOP SECRET information. Four modes of AES were implemented: Counter with Cipher Block Chaining Message Authentication Code (CCM), Galois/Counter Mode (GCM), Synthetic Initialization Vector (SIV) and EAX. SIV and EAX are highly specialized AE techniques designed for specific problems. SIV and EAX are currently under consideration for use in a classified environment and were included in the NPS UAV ODroid processor performance analysis. In addition, ChaCha20-Poly1305 was implemented, an unstandardized AE algorithm. The ChaCha20 algorithm for encryption and Poly1305 for authentication have become a popular alternative in industry for performing AE. In 2014, Google replaced AES-GCM on its Android phones with ChaCha20-Poly1305, believing it to more secure and showing it to be significantly faster in software implementations. This is used as a baseline for securing swarm communications that is unclassified.

Table 2. Effects of cryptographic operations on throughput

Cryptographic Algorithm	**Average Throughput (kbps)**	**Maximum Throughput (kbps)**	**Average Overhead Incurred (%)**
None	44.23	60.28	0
CCM	53.29	71.64	20.4
GCM	54.29	72.82	22.5
ChaCha20-Poly1305	56.73	76.96	28.2

To analyze these AE algorithms, three instances of UAVs using multi-UAV simulation in the loop (SITL) software were created, commanded and flown with actual flight software. The messages passed between UAVs and ground station were the same as though the UAVs had been flying. Traffic is dominated by just three types of messages: Pose, Flight Status and Heartbeat. Table 2 shows the effects of AE on swarm throughput. ChaCha20-Poly1305 had the greatest overhead. Note that the bytes per message overhead incurred by each algorithm is constant, regardless of message length. Thus as message length increases, the overhead as a percentage of message length due to cryptographic operations decreases. To completely understand the impact of AE on the swarm, it is necessary to determine if the ODroid processor is capable of sustaining the cryptographic overhead incurred. To make this determination, GCM, CCM, SIV, EAX and ChaCha20-Poly1305 algorithms were implemented and executed on the ODroid hardware.

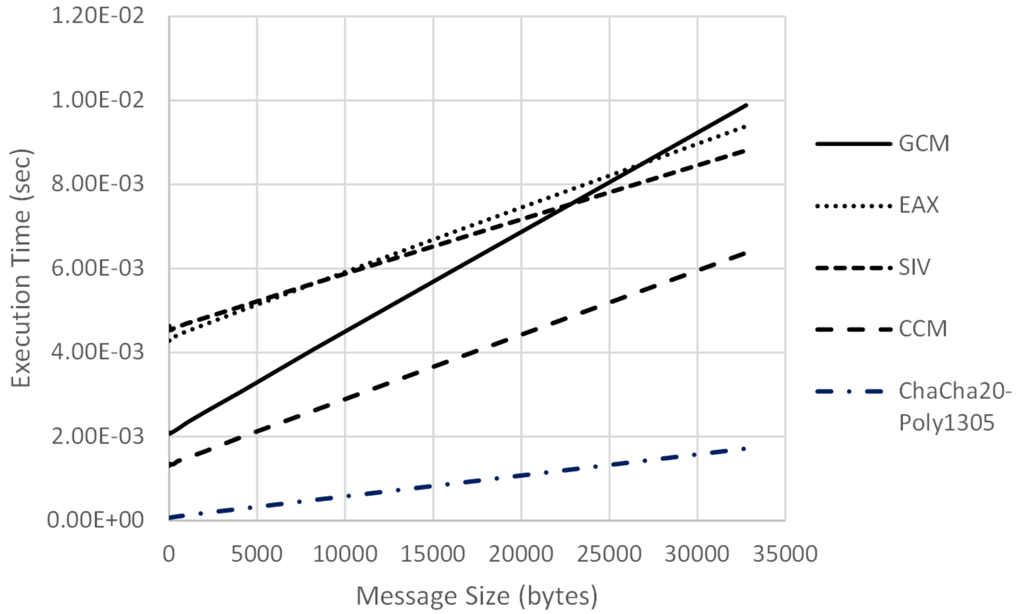


Figure 26. NPS UAV ODroid performance while executing cryptographic operations with 256 bit key sizes for the 5 AE algorithms

AE was performed on messages of sizes ranging from 8 to 32,768 bytes and then decrypted and authenticated. For each message size, this step was repeated 10,000 times and averaged. Each message was randomized on each pass to create as cold a cache as possible. The experiment was repeated with key sizes of 128, 192 and 256 bits (*see Figure 26*). ChaCha20-Poly1305 and SIV do not provide functionality for key sizes of 128 and 192 bits. According to the results, CCM outperformed GCM. As was expected, the best performance for any key size was ChaCha20-Poly1305. EAX and SIV had the poorest overall results.

Table 3. Cryptographic times for average sized message in milliseconds

	128 Bit Key	192 Bit Key	256 Bit Key
CCM	1.30	1.31	1.32
ChaCha20-Poly1305			.0781
EAX	4.40	4.28	4.33
GCM	2.10	2.08	2.09
SIV			4.54

Another interesting result is how little key size affects speed of execution, especially with smaller messages. The average length of an unencrypted message was 141.61 bytes. Table 3 lists the average time (in milliseconds) to execute each iteration of an average length message. The burden that cryptography will place on the ODroid computer can be predicted from the channel throughput analysis. Analysis suggests that SIV and EAX would not be able to support a 50 UAV swarm, as the ODroid would be spending 100% of its time on cryptographic operations and still not be able to keep up with the traffic load. GCM and CCM might be able to manage an average case load in a 50 UAV swarm, but it would be consuming a significant amount of the processing capacity, leaving little to other processes. Due to space, figures that depict these results are not included in this summary. Currently, the swarm at NPS is used for academic purposes. It does not gather or create classified information and thus does not require the use of an AES based algorithm. The performance was analyzed when AE was performed on command data only. With this mitigation, SIV and EAX still fall short of acceptability on large swarms. GCM and CCM perform tolerably and ChaCha20-Poly1305 gives the superior performance. Again due to space, figures that depict these results are not included in this summary. Parts of this work have been accepted for publication in the IEEE International Symposium on Network Computing and Applications (NCA) 2016 Conference to be held in Boston in November 2016. Many results of this research are published in this paper. In addition to the hardware experiments discussed above, an NS-3 model of the UAV channel is currently simulating in software. This will allow a more in depth understanding of how much capacity is actually available. It will be able to model how distance, packet collision avoidance and modulation affect throughput. The analysis of the results from the NS-3 model will be completed by the end of October 2016.

POC: Dr. Preetha Thulasiraman (pthulas1@nps.edu)

30. Tactical Aerial Resupply with Extended Standoff Range

The U.S. Marine Corps (USMC) envisions a future operating force where small elements of Marines will operate in multiple, dispersed locations along the littorals. The lines of communication required to sustain these maneuvering forces, whether by land or air, are vulnerable to enemy disruption. The U.S. Army / Air Force Joint Precision Airdrop System (JPADS) program conducted in 2001-2013 resulted in fielding several different-weight systems capable of precise delivery of supplies to distributed forces. Touchdown accuracy for these systems heavily depends on the payload weight (size of the system), winds aloft, surface-layer winds and terrain, resulting in landing accuracies ranging from ~70m to 250m circular error probable (CEP). The standoff range is limited by the performance of ram-air parafoils these systems employ, usually not exceeding 3:1 glide ratio (with respect to the air). The high costs of ram-air parachute canopies and airborne guidance units (AGUs) employed by JPADS, drive the overall cost of JPADS to be of the order of $25K for small systems, all way up to $100K for larger systems, thereby requiring retrieval and return of parafoil system in order to maintain fiscal feasibility at the expense of significant workload increase for combat personnel.

This research effort elaborated on the previous experience and used inexpensive commercial technologies to develop a prototype of a tactical resupply delivery system for USMC that could increase military utility and drastically reduce costs. A novel approach to provide a Marine rifle squad with one-day sustainment is based on utilizing relatively inexpensive disposable gliders as opposed to expensive and difficult to maintain ram-air parachute canopies. This alternative is thought to improve logistics, assure higher glide ratios (standoff distances) and better wind penetration (touchdown accuracy).

The research included the conceptual and then detailed design and manufacturing of retractable high-aspect-ratio wing attachment to be mounted on top of payload container. As an example, Fig.1a shows the developed attachment mounted atop a Pelican 1200 container (other trials involved a Pelican 1600-size container). Figure 1b demonstrates a complete assembly including a proper-size foam wings (that were manufactured in-situ at the test site).

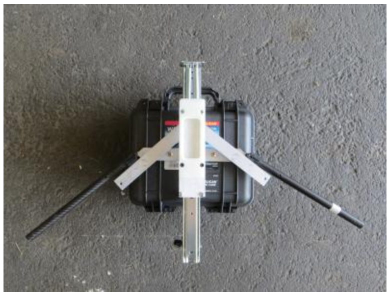
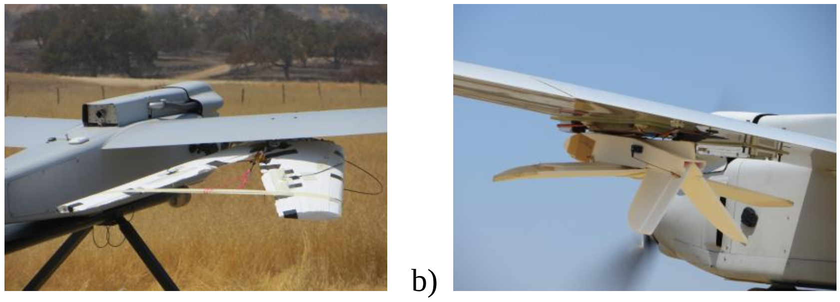
a)  b) 

Figure 27. Simple attachment to a payload casing (a) and fully assembled system (b).

The entire system is spring loaded and can be deployed from any carrier (transport aircraft, helicopter or unmanned aerial vehicle (UAV)). Upon deployment the spring mechanism gradually opens the wings out (to avoid a dynamic shock if being deployed at high speeds).

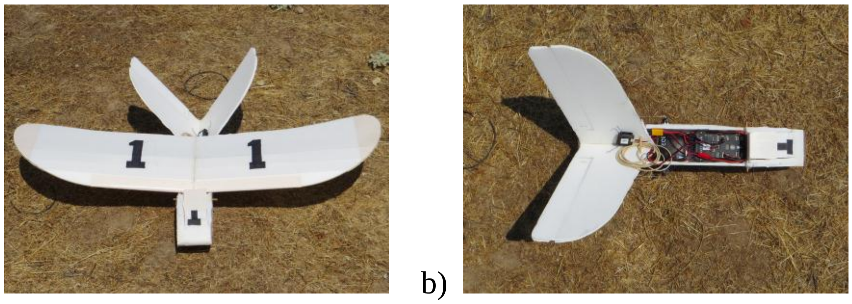
The developmental field experiments were conducted at Camp Roberts, CA and involved using a Tier II Arcturus T-20 UAV as a carrier platform. Figure 16a illustrates the developed system hanged under the wing of T-20 UAS sitting on a catapult launcher. Experiments included deploying the developed system from a straight level flight at 2’000 ft above the ground. The preliminary tests of a developed prototype were primarily aimed at verifying a mechanical design and assuring reliability of deploying a payload delivery glider from UAV.

In parallel, even a smaller glider, made entirely from a foam board, was developed and equipped with commercial-of-the-shelf (COTS) avionics (as opposed to a custom-designed AGU) to investigate guidance, navigation and control (GNC) algorithms to be later scaled up to be implemented on the aerial payload delivery glider. The goal of testing this smaller system was to achieve at least a 5:1 glide ratio (to meet the objectives set forward by USMC) and enable safe landing within the threshold value of 150ft CEP and later on within the objective value of 50ft CEP. To date, several designs and several GNC solutions were tested. Figure 3a shows one of these designs and Figure 17b features its avionics bay hosting a Pixhawk autopilot (another autopilot was investigated as well). This foam glider was also deployed from a T-20 UAV and assumed an upside-down mounting (*see Figure 27b*).



a) b)

Figure 28. Prototype of glider delivery system (a) and GNC testbed glider (b) under the wing of Tier II UAV.



a) b)

Figure 29. GNC testbed glider (a) and its avionics bay (b).

The research effort involved four MS students from two departments of NPS' engineering school and three graduate students from the University of Missouri at Kansas City.

More tests are scheduled to be carried out in October-December of 2016.

POC: Dr. Oleg Yakimenko (oayakime@nps.edu)

31. MATLAB Interface for Mobile Robots

Within the field of robotics, there is the need for a programming and interface utility in which to build and develop robot applications. Over the years, many solutions have been developed for this, and perhaps the most successful and widely used is the Robot Operating System (ROS) from Willow Garage. ROS is a collection of open-source libraries and tools and has become the standard for robotics engineers and researchers worldwide. Its architecture facilitates the collaboration of researchers through the use of packages that are available for download from their websites. In spite of its versatility and world-wide popularity, however, ROS requires a certain degree of experience that is only obtained after a dedicated effort to learn how to employ its features and utilities.

For teaching an introductory course to engineering students who are pursuing studies in other areas outside of robotics, for example, electromagnetics, power electronics, signal processing, and communications, a robot interface utility was needed that was easy to use and leveraged student's existing programming skills. Most engineering students around the world are exposed to MATLAB at one point or another. Certainly, this is the case at NPS. As a solution, this research project developed an interface for the P3-DX mobile robot from Adept Mobile Robots. This utility is entirely based within MATLAB and is easy to use, thus providing a low barrier for entry into robotics or simply for those who only wish to take a one-time course on the subject.

The interface consists of a library of MATLAB functions that handle all of the low-level communications and control of the P3-DX robot. These functions are enabled via the MATLAB command line or may be integrated into a user script for more advanced robot behavior. Since the functions are written in the MATLAB environment, consequently, they are highly portable to any MATLAB supported platform, including Windows, Mac, and Linux.

Student response has been very positive as they use the interface to carry out lab assignments in the ECE introductory robotics course. The interface allows students to focus on studying robotics concepts, such as, navigation, motion planning, and mapping without the added burden of learning a new programming language or environment.

CRUSER has been kind enough to support the development of the interface, as this research team works to develop additional features for the utility. More recently, the MATLAB interface has been expanded to include a scanning laser, with future work focused to expand the interface to work with other robots within the P3 family, such as the P3-AT robot for outdoor use and the smaller Amigo robot.

POC: Dr. Xiaoping Yun (xyun@nps.edu) and James Calusdian

B. EDUCATIONAL ACTIVITIES

The primary mission of the NPS is to provide relevant and unique advanced education and research programs to increase the combat effectiveness of commissioned officers of the Naval Service to enhance the security of the United States. CRUSER's core mission is to "shape generations of naval officers through education, research, concept generation and experimentation in maritime application of robotics, automation, and unmanned systems." CRUSER education programs consist primarily of science, technology, engineering, and math (STEM) outreach events; support for NPS student thesis work; and a variety of education initiatives. These initiatives include sponsored symposia that address ethical questions and related critical issues, catalog degree programs, short courses, and certificate programs. CRUSER's support of educational activities also involves surveying and aligning curricula for interdisciplinary unmanned systems education.

1. Education Track Funded Projects

Project summaries for CRUSER supported educational activities (*see Table 2*) are included in the previous section.

Table 4. CRUSER supported Education Track projects, FY16 (alphabetical by principal investigator last name)

PROJECT TITLE	PRINCIPAL INVESTIGATOR
RoboDojo	Buettner/Tsolis
Agent Library of Unmanned Vehicles	Giachetti
Unmanned Systems Grasping: A Laboratory Based around Arm Grasping	Harkins
Applications of a mobile acoustic source for Tactical Oceanography	Joseph
Towards Autonomous ISR missions by a team of cooperating Gliders	Kaminer
CRUSER Data Farming Workshops	Sanchez
Robotic system software engineering classroom case study	Shebalin
Future Challenges for Just War Theory: International Conference	Strawser
Development of instructional tutorials, online wiki, and videos in support of Robotics and Rapid Prototyping	Whitcomb/Tsolis
Development of Control System Course Content for Interdisciplinary Applications in Robotics	Yakimenko

2. NPS Course Offerings and Class Projects

Select NPS courses contribute to CRUSER's mission by conducting class projects in various aspects of unmanned systems employment. Unmanned systems are studied directly, or introduced as a technical inject for use in strategic planning or war gaming. Beyond advancing research and concept development, these projects enhance education in unmanned systems. Capstone project courses are listed first. Other courses are listed alphabetically by course code.

a. Systems Engineering Analysis (SEA)

Sponsored by the CNO Warfare Integration Division Chair of Systems Engineering Analysis, this inter-disciplinary curriculum provides a foundation in systems thinking, technology and operations analysis for warfighters. Each cohort must produce a report detailing their research, and make a recommendation based on their findings.

SEA 23 PROJECT SUMMARY: The proliferation of land and sea based platforms capable of projecting a highly sophisticated, effective and integrated anti-access, area-denial environment poses a significant problem for the U.S. Navy. In these environments, the current fleet methods for tactical offensive operations from the sea are frequently deemed high-risk (i.e. carrier strike groups) or incapable of projecting sufficient power (i.e. a small surface action group). The need for resilient strike capabilities in a high-risk combat environment, results in capability gaps that exist with current systems. The Systems Engineering Analysis Cohort 23 (SEA23) was tasked with developing a system of systems (SOS) to integrate cross-domain naval fires in these combat situations, with potential for fielding in the 2025-2030 period.

Tasking from the project sponsor, OPNAV N9I (Deputy Director for Warfare Integration), was broad in scope; however, with stakeholder analysis, SEA23 focused on the communication of fire control data between a forward sensing platform to a firing platform. The project team explored and analyzed multiple manned and unmanned systems and tactical data link networks that can be suitable in the requested period, and pared down the original tasking statement:

SEA23 will investigate a concept of operations in a contested environment using modular unmanned and manned platforms capable of carrying communications and data suites to enable cross-domain targeting information in support of tactical offensive operations in a contested, denied, degraded, intermittent, and limited bandwidth environment (DDIL).

SEA23 made critical assumptions to scope the project, and enabled completion in a nine-month period. The first major assumption is that the degradation of GPS will be graceful. In addition, alternate methods of precision navigation and time exist for weapons targeting. The second major assumption is scenario based, in that the surface action group employed for assessing system alternatives consists of three Arleigh Burke class guided missile destroyers, allowing exploration into the concept of distributed lethality (Rowden, et al. 2015). Finally, the system needs to rely on line-of-sight relay to overcome DDIL challenges. This situation is a good application for mesh networking due to their dynamic and ad hoc nature. In a changing environment, “the ability of self-organization, self-discovering, self-healing, and self-configuration” (Misra et al. 2009) inherent in mesh networks is highly prized. These assumptions enabled the research efforts to focus on the network architecture, type and requisite supporting platforms.

Unmanned aerial vehicles (UAVs) were determined to be the best systems to structure a tactical targeting relay network in the DDIL environment to achieve long range line-of-sight capabilities. Near fully autonomous UAVs carry the proposed network hardware operating collectively in order to support a mesh network.

Bounding the mesh network to line-of-sight communications establishes the system requirements for UAV separation, operational altitude, power requirements for transmission, payload capacity, and needed reliability, availability and maintainability. They recommended an architecture based on Link 16 and organic rotary wing unmanned aerial vehicles to transfer sensor to shooter data in demanding and contested environments.

<u>SEA 24 PROJECT SUMMARY</u>: Along with CDR Kevin Williams (USW-OR ’16) thesis focused on the same topic, the SEA 24 will investigate a systems of systems (SoS) centered around the P-8A Poseidon and the Coyote® Unmanned Targeting Air System (UTAS) with MAD sensor in an attempt to reduce the time to Find, Fix, Track, Target, and Engage (F2T2E) a

submarine while carefully considering cost, operator task saturation, P-8A sonobouy storage capacity, and projected technological advancements in the 2025-2030 timeframe to ensure each system architecture is a viable system in support of High Altitude ASW (HAASW) operations. This work will be completed in the Fall of 2016.

POCs: Professor Jeff Kline (jekline@nps.edu), Dr. Gary Langford (golangfo@nps.edu)

b. Introduction to Scientific Programming (AE2440)

The Introduction to Scientific Programming course offers an introduction to computer system operations and program development. The main goal of this course is to provide an overview of different structured programming techniques, along with introduction to MATLAB/Simulink and to use modeling as a tool for scientific and engineering applications. Among others the course teaches techniques for rapid prototyping of mission building / control development for unmanned vehicles.

POC: Professor Oleg Yakimenko (oayakime@nps.edu)

c. Robotic Multibody Systems (AE4820)

This course focuses on the analytical modeling, numerical simulations and laboratory experimentation of autonomous and human-in the loop motion and control of robotic multibody systems. Systems of one or more robotic manipulators that are fixed or mounted on a moving vehicle are treated. Applications are given for under-water, surface, ground, airborne, and space environments. The course reviews basic kinematics and dynamics of particles, rigid bodies, and multibody systems using classical and energy/variational methods. The mechanics and control of robotic manipulators mounted on fixed and moving bases are considered. The course laboratories focuses on analytical and numerical simulations as well as hands-on experimentation on hardware-in-the-loop.

POC: Dr. Marcello Romano (mromano@nps.edu)

d. Fundamentals of Robotics (EC4310)

This course presents the fundamentals of land-based robotic systems covering the areas of locomotion, manipulation, grasping, sensory perception, and tele-operation. Main topics include kinematics, dynamics, manipulability, motion/force control, real-time programming, controller architecture, motion planning, navigation, and sensor integration. Several Nomad mobile robots will be used for class projects. Military applications of robotic systems are discussed.

POC: Professor Xiaoping Yun (yun@nps.edu)

e. Introduction to Control Systems (ME2801)

The Introduction to Control Systems presents classical analysis of feedback control systems of dynamic systems including unmanned vehicles using basic principles in the frequency domain and in the s-domain. Performance criteria in the time domain such as steady-state accuracy, transient response specifications, and in the frequency domain such as bandwidth and disturbance rejection are introduced. Simple design applications using root locus and Bode plot techniques are addressed. Laboratory experiments are designed to expose the students to testing and evaluating mathematical models of physical systems, using computer simulations and hardware implementations.

POC: Dr. Brian Bingham (bsbingha@nps.edu)

f. Introduction to Unmanned Systems (ME3720)

An Introduction to Unmanned Systems is an introductory graduate level course in robotics with an emphasis on learning through hands on projects. It provides an overview of unmanned aerial, surface and underwater systems technology and operations including guidance, navigation, control, sensors, filtering and mapping. All three class projects currently use a small dual water jet USV as the demonstration robot. Each project is broken down into simulation and operation sections. The first project involves the implementation of a Proportional, Integral and Derivative heading controller. The second project goal is to design and implement a cross track error controller. The final project involves real-time path planning and path following through a dynamically changing environment. Course work includes programming the robot in python.

POC: Dr. Douglas Horner (dphorner@nps.edu)

g. Autonomous Systems and Vehicle Control II (ME4811)

This course introduces multivariable analysis and control concepts for MIMO systems. Topics covered include: state observers, disturbances and tracking systems, linear optimal control, and the linear quadratic Gaussian compensator. The course also gives an introduction to non-linear system analysis, and limit cycle behavior.

POC: Dr. Isaac Kaminer (kaminer@nps.edu)

h. Marine Navigation (ME4821)

The Marine Navigation course presents the fundamentals of inertial navigation, principles of inertial accelerometers and gyroscopes. It also considers external navigation aids (navaids) including the Global Positioning System (GPS). This course includes derivation of gimbaled and strapdown navigation equations and error analysis. It also introduces Kalman filtering as a means of integrating data from navaids and inertial sensors. Students are required to model navigation system and test it in computer simulations as applied to a choice of underwater, surface, ground or aerial vehicle in the ideal and GPS-denied environment.

POC: Professor Oleg Yakimenko (oayakime@nps.edu)

i. Guidance, Navigation, and Control of Marine Systems (ME4822)

This course takes students through each stage involved in the design, modeling and testing of a guidance, navigation and control (GNC) system. Students are asked to choose a marine system such as an AUV, model its dynamics on a nonlinear simulation package such as SIMULINK and then design a GNC system for this system. The design is to be tested on SIMULINK or a similar platform. Course notes and labs cover all the relevant material.

POC: Dr. Isaac Kaminer (kaminer@nps.edu)

j. Cooperative Control of Multiple Marine Autonomous Vehicles (ME4823)

This course covers selected topics on trajectory generation and control of multiple marine autonomous vehicles. First part of the course addresses techniques for real-time trajectory generation for multiple marine vehicles. This is followed by introduction to algebraic graph theory as a way to model network topology constraints. Using algebraic graph theory formalism Agreement and Consensus problems in cooperative control of multiple autonomous vehicles are discussed, followed by their application to cooperative path following control of multiple autonomous vehicles. Lastly, the course covers topics suggested by the students, time permitting.

POC: Dr. Isaac Kaminer (kaminer@nps.edu)

k. Leadership in Product Development (MN3108)

This is a product development course providing a broad framework for the leadership of end-to-end product commercialization with a student hands-on design challenge, to give students perspective and appreciation for the critical success factors and inhibitors to successful commercialization of complex products and systems. The format includes lectures, guest speakers, case studies and a design challenge. Topics include product development strategy and leadership, the front-end process, product delivery, distribution and customer support. The Design Challenge is as a multi-disciplinary system design experience. Students work in teams to design, build, test and demonstrate a real product, which in FY16 was a self-driving car autonomous system. The Design Challenge culminates with a prototype demonstration competition. (Kristin Giammarco and Wally Owen instructing)

POC: Associate Professor Kristin Giammarco (kmgiamma@nps.edu)

l. Search Theory and Detection (OA3602)

Students in this course, Search Theory and Detection (OA3602) investigated the mathematical and computational foundations of applied probability, stochastic systems, and optimization modeling in relation to operationally relevant search scenarios, such as anti-submarine warfare, mine clearance and sweeping, and combat search and rescue. Such mission sets, to also include intelligence, surveillance, and reconnaissance (ISR); harbor security; and border patrol, are increasingly involving unmanned systems.

POC: Professor Michael Atkinson (mpatkins@nps.edu)

m. Joint Campaign Analysis (OA4602)

The Joint Campaign Analysis course is an applied analytical capstone seminar attended by operations research students, joint operational logistics students, modeling and simulation students, and systems engineering analysis students. It uses scenarios and case studies for officers to use the skills they have acquired in their degree programs in an operational environment. During scenario planning and quantitative assessment using warfare analysis techniques, students are asked to provide a quantitative military value assessment of unmanned systems and their concept of employment. In a Maritime War 2030 scenario involving increased tensions and conflict in the Sea of Okhotsk, East China Sea, and Baltic Sea, students explored demanding sea control environments and the use of unmanned systems to enhance cross domain integrated fires in those environments For example, when Precision, Navigation, and Timing information is constrained, DARPA's TERN project (longrange UAV from Surface Action Group) was shown to provide longer range targeting capability and more efficient use of missiles.

POC: Professor Jeff Kline (jekline@nps.edu)

n. Advanced Applied Physics Lab (PC4015)

Students incorporate knowledge of analog and digital electronic systems to design, implement, deploy and demonstrate an autonomous vehicle. The vehicle is required to demonstrate navigation and collision avoidance. The course is taught in a standard 12-week format. A Needs Requirement Document is presented. Design reviews are held at the 4 and 8 week period. Demonstration of Autonomy is required to pass the class.

POC: Professor Richard M. Harkins (rharkins@nps.edu)

o. *Systems Architecture and Design (SE4150)*

This course provides students an opportunity to develop and practice system architecting and design skills in identifying system elements with their capabilities, designing the relationships between those elements, and predicting system behavior through those relationships. The course provides the language, terminology, concepts, methods, and tools of system architecting, modeling and design through a study of various types of architectures, architecting and design. Through the use of "A Lab Manual for Systems Architecting and Analysis," which sets an operational stage for the employment of manned or unmanned systems for search and rescue operations, students explore functional and physical architecture modeling and analysis, architecture frameworks, and object oriented modeling approaches. (Warren Vaneman instructing)

POC: Associate Professor Kristin Giammarco (kmgiamma@nps.edu)

p. *Systems Integration and Development (SE4151)*

This course provides the student with an understanding of the context and framework for planning and carrying out integration and development, including emergent behavior, manufacturing, and production of complex systems. Topics covered include systems and SoS integration and production with consideration of multiple suitability aspects, including availability, reliability, maintainability, embedded software, human factors, producibility, interoperability, supportability, emergent behavior, life cycle cost, schedule, and performance. The CRUSER-sponsored "Lab Manual for Systems Architecting and Analysis" was used to provide students with a reference operational mission of search and rescue, as well as design and integration techniques for assessing manned and unmanned solutions for executing that missions. (Kristin Giammarco instructing)

POC: Associate Professor Kristin Giammarco (kmgiamma@nps.edu)

q. *Systems Test and Evaluation (SE4354)*

The Systems Test and Evaluation course covers principles of test and evaluation (T&E) and the roles, purposes, functions, and techniques of T&E within the systems engineering process. The course covers all aspects of T&E throughout the life cycle of a system to include test planning, test resources, development of test requirements, selection of critical test parameters, development of measures of effectiveness and performance, test conduct, analysis of test results, and determination of corrective action in the event of discrepancies. It also covers principles of experiment design and statistical analysis of test results. Students are also exposed to several case studies and lessons learned from actual defense system tests.

POC: Professor Oleg Yakimenko (oayakime@nps.edu)

r. *Formal Methods for Systems Architecting (SE4935)*

This course debuted in Spring 2015 to introduce the application of formal methods to system architecture model and design analysis. PhD and Master's students were exposed to theories and practices that use mathematics and formal logic for the formulation, interrogation, assessment and measurement of properties of architecture models and the designs they describe. Unmanned system models in the Monterey Phoenix -enabled tool at firebird.nps.edu, all CRUSER-sponsored works, were introduced along with conventional modeling techniques illustrated in the "Lab Manual for Systems Architecting and Analysis," which was sponsored by CRUSER in FY14. The aim of this course is to apply systematic and formal thinking to the development and evaluation of system architectures. Students completed individual projects demonstrating their understanding of new architecting principles and practices developed for unmanned systems models, and many went on to synthesize potential PhD research topics from their papers. The creation of this course was wholly-enabled by the products of the 2015 CRUSER research and the 2016 course offering informed the development of educational manuals. (Kristin Giammarco instructing)

POC: Associate Professor Kristin Giammarco (kmgiamma@nps.edu)

s. *Model Based Systems Engineering (SE4930)*

Practical systems engineering relies heavily on models during conceptualization, system definition, system design, system integration, as well as system assessment. This course addressed the use of models in all phases of the systems engineering process using the CRUSER-sponsored "A Lab Manual for Systems Architecting and Analysis" as a student learning guide. The lab manual guided the team projects to design a UGV. Another section of SE4930 students during the same term were exposed via a guest lecture to unmanned systems modeled in Monterey Phoenix. (Kristin Giammarco instructing / Gene Paulo instructing)

POC: Associate Professor Kristin Giammarco (kmgiamma@nps.edu)

t. *Systems Software Engineering (SE4003)*

This course is designed to teach students the basic concepts of software engineering and methods for requirements definition, design and testing of software. Specific topics include introduction to the software life cycle, basic concepts and principles of software engineering, object-oriented methods for requirements analysis, software design and development. Special emphasis is placed on the integration of software with other components of a larger system. In the FY16 class, students from NAVAIR learned how to model and test the systems software architecture of a UGV using automated tools including Innoslate and Monterey Phoenix (MP). Four MP assignments were assigned and completed to teach students the basics of using this tool for exposing design errors in the CRUSER-sponsored UGV case study. (Kristin Giammarco instructing)

POC: Associate Professor Kristin Giammarco (kmgiamma@nps.edu)

u. Systems Architecture (SI4022)

Systems architects respond to user needs, define and allocate functionality, decompose the system, and define interfaces. This course presents a synthetic view of system architecture: the allocation of functionality and its projection on organizational functionality; the analysis of complexity and methods of decomposition and re-integration; consideration of downstream processes including manufacturing and operations. Physical systems and software systems, heuristics and formal methods are presented. Students attended a lecture on Monterey Phoenix, including a demo of unmanned system models, and many students in this section chose to conduct their individual research assignments in the area of systems architecting using techniques described in the CRUSER-sponsored "Lab Manual for Systems Architecting and Analysis." (Kristin Giammarco instructing)

POC: Associate Professor Kristin Giammarco (kmgiamma@nps.edu)

3. NPS Student Theses

CRUSER community of interest members guided several NPS students as they developed and completed their thesis work throughout the CRUSER program lifetime (*included in a cumulative listing in Appendix B*). The following table (see Table 3) lists students mentored in FY16, as well as those who graduated in September 2015 as their thesis work was still in academic processing when the FY15 CRUSER report was released in October 2015.

Table 5. FY16 CRUSER mentored NPS student theses (*reverse chronological by release date*)

AUTHOR(s)	TITLE	DATE (year-mo)	URL
Sean X. Hong	Phased array excitations for efficient near field wireless power transmission	2016-09	
LT David Armandt USN	Controlling robotic swarm behavior utilizing real-time kinematics and artificial physics	2016-06	http://hdl.handle.net/10945/49465
ENS Eric B. Bermudez USN	Terminal homing for autonomous underwater vehicle docking	2016-06	http://hdl.handle.net/10945/49385
Capt. Jerry V. Drew II USA	Evolved design, integration, and test of a modular, multi-link, spacecraft-based robotic manipulator	2016-06	http://hdl.handle.net/10945/49446

LTJG Alejandro Garcia Aguilar Mexican Navy	CFD analysis of the SBXC Glider airframe	2016-06	http://hdl.handle.net/10945/49466
CMDR Andrew B. Hall USN	Conceptual and preliminary design of a low-cost precision aerial delivery system	2016-06	http://hdl.handle.net/10945/49478
LTJG Serif Kaya Turkish Navy	Evaluating effectiveness of a frigate in an anti-air warfare (AAW) environment	2016-06	http://hdl.handle.net/10945/49504
SEA 23 Cohort	Unmanned systems in integrating cross-domain naval fires	2016-06	http://hdl.handle.net/10945/49381
Capt. Matthew S. Zach USMC	Unmanned tactical autonomous control and collaboration coactive design	2016-06	http://hdl.handle.net/10945/49417
LCDR Jose R. Espinosa Gloria Mexican Navy	Runway detection from map, video and aircraft navigational data	2016-03	http://hdl.handle.net/10945/48516
LT Matthew S. Maupin USN	Fighting the network: MANET management in support of littoral operations	2016-03	http://hdl.handle.net/10945/48561
LCDR Brian M. Roth USN and LCDR Jade L. Buckler USN	Unmanned Tactical Autonomous Control and Collaboration (UTACC) unmanned aerial vehicle analysis of alternatives	2016-03	http://hdl.handle.net/10945/48586
LT Manuel Ariza Colombian Navy	The design and implementation of a prototype surf-zone robot for waterborne operations	2015-12	http://hdl.handle.net/10945/47847
LT Loney R. Cason III USN	Continuous acoustic sensing with an unmanned aerial vehicle system for anti-submarine warfare in a high-threat area	2015-12	http://hdl.handle.net/10945/47918
LT Ross A. Eldred USN	Autonomous underwater vehicle architecture synthesis for shipwreck interior exploration	2015-12	http://hdl.handle.net/10945/47940
LT Robert T. Fauci III USN	Power management system design for solar-powered UAS	2015-12	http://hdl.handle.net/10945/47942
LCDR Oscar García Chilean Navy	Sensors and algorithms for an unmanned surf-zone robot	2015-12	http://hdl.handle.net/10945/47949
SE Team Mental Focus	A decision support system for evaluating systems of undersea sensors and weapons	2015-12	http://hdl.handle.net/10945/47868

SE Team Mine Warfare 2015	Scenario-based systems engineering application to mine warfare	2015-12	http://hdl.handle.net/10945/47865
SE Team TECHMAN	Systems engineering of unmanned DoD systems: following the Joint Capabilities Integration and Development System/Defense Acquisition System process to develop an unmanned ground vehicle system	2015-12	http://hdl.handle.net/10945/47867

To aid new NPS students in their search for viable thesis topics, CRUSER maintains an iterative listing of potential thesis topics related to unmanned systems.

4. NPS Student Travel

CRUSER supported 34 NPS student trips in FY16 to further their thesis work (*see Table 6*). NPS students were then required to give a trip report at a monthly NPS CRUSER meeting to further socialize their work. Additional student trips were funded out of individual project funds.

Table 6. CRUSER supported student travel, FY16

Date	Student
September-16	LT Ryan Beall, USN
September-16	LCDR Drew Barker, USN
July-16	LCDR Matthew O'Brian, USN
August-16	Maj T. Kulisz, USMC Capt Robert Sharp, USMC
August-16	Capt Michael Wilcox, USMC
July-16	LT Chaz Henderson, USN
July-16	LCDR Jake Jones, USN
July-16	LT Nicholas Manzini, USN
July-16	LT Ian Taylor, USN
July-16	LT Peter Tydingco, USN
June-16	LT Christopher McCook, USN
June-16	CDR Kathleen Giles, USN
May-16	Maj Robert Lingler, USMC
May-16	SFC Fritz M., USA
May-16	SFC, Watts J., USA
May-16	GYSgt, Cheeseboro W., USMC
May-16	Faulkner, C
May-16	Golliver, J
May-16	Montero, C
May-16	SFC Polanco A., USA
May-16	SFC Schollett B., USA
May-16	Thomas, A
May-16	Henderson, C

May-16	Torres, M
April-16	Zach, M
April-16	Kirkpatrick, T
April-16	Larreur, C
April-16	Rushing, E
April-16	Recalde, W
April-16	Beierl, C
April-16	Connors, J
April-16	Kline, T
April-16	Teichert, E

C. CONCEPT GENERATION

The first NPS Innovation Seminar supported the CNO sponsored *Leveraging the Undersea Environment* wargame in February 2009. Since that time, warfare innovation workshops have been requested by various sponsors to address self-propelled semi-submersibles, maritime irregular challenges, undersea weapons concepts and general unmanned concept generation. Participants in these workshops include junior officers from NPS and the fleet, early career engineers from Navy laboratories, academic and industry partners, and NWC Strategic Studies Group (SSG) Director Fellows.

1. Warfare Innovation Workshops

The first CRUSER sponsored Warfare Innovation Workshop (WIW) was in March 2011, shortly after the formal launch of the Consortium. Since that time CRUSER has sponsored seven complete workshops covering topics of interest to a wide variety of the full community of interest, and has generated nearly 500 technology and employment concepts. Workshops to date include:

1. Future Unmanned Naval Systems (FUNS) Wargame Competition, March 2011
2. Revolutionary Concept Generation from Evolutionary UxS Technology Changes, September 2011
3. Advancing the Design of Undersea Warfare, September 2012
4. Undersea Superiority 2050, March 2013
5. Distributed Air and Surface Force Capabilities, September 2013
6. Warfighting in the Contested Littorals, September 2014
7. Unmanned Maritime Systems Life Cycle Costing, March 2015
8. Creating Asymmetric Warfighting Advantages, September 2015

9. Developing Autonomy to Strengthen Naval Power, September 2016

Our most recent workshop, Developing Autonomy to Strengthen Naval Power, was held 19-22 September 2016 on the NPS campus. This workshop included just over 90 participants representing a wide variety of stakeholder groups.

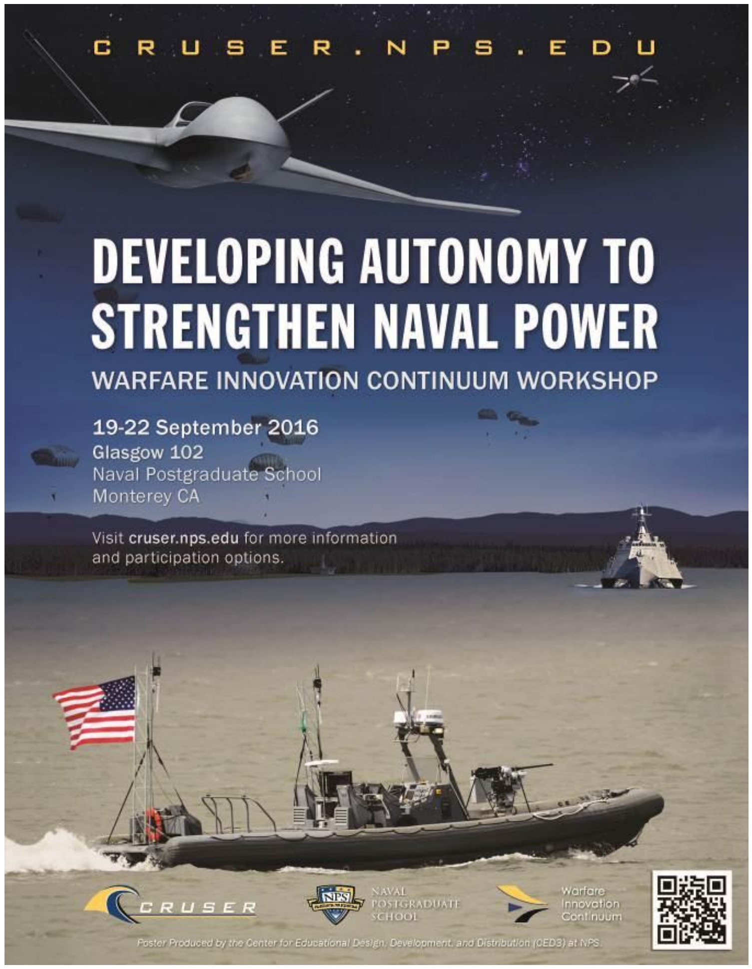


Figure 30. September 2016 Warfare Innovation Continuum (WIC) Workshop, "Developing Autonomy to Strengthen Naval Power"

To support the first line of effort stated in the guidance promulgated by the Chief of Naval Operations in January 2016, the 2016 WIC Workshop explored robotics and autonomous systems – in particular how increased autonomy will enhance alternative fleet designs, including kinetic and non-kinetic payloads and both manned and unmanned systems. This effort considered new naval platforms and formations – in a highly "informationalized" environment – to meet combatant commander needs. Small teams of junior officers from NPS and the fleet, and early career engineers from Navy labs, academia and industry proposed technologies and employment concepts in scenario based discussions.

Figure 31. September 2016 Warfare Innovation Continuum (WIC) Workshop

Participants included NPS students from across campus, as well as guests from Navy labs, other DoD commands, academia and industry. After a morning of knowledge-leveling plenary briefings, team participated in an innovation seminar based on user centered design developed in Silicon Valley. Teams spent the next two days generating concepts to enhance future warfighting in an urban littoral environment, and presented their chosen concepts on Thursday morning. All participants earned Continuing Education Credits (CEUs) from the Naval Postgraduate School for this event. CEUs will be awarded as part of CRUSER's education mandate for any CRUSER activity that meets applicable academic guidelines.

CRUSER and Warfare Innovation Continuum leadership reviewed all the proposed concepts and selected ideas with potential operational merit that aligned with available resources. All these concepts are described fully in the September 2016 Warfare Innovation Continuum (WIC) Workshop final report (limited distribution).

Selected concepts will begin CRUSER's sixth Innovation Thread, and members of the CRUSER community of interest will be invited to further develop these concepts in response to the FY17 Call for Proposals. A final report detailing process and outcomes will be released before the end of the 2017 calendar year to a vetted distribution list of leadership and community of interest members. Technical members of the CRUSER community of interest will make proposals to explore concepts in lab or field environments.

2. CRUSER Technology Continuum (TechCon), July 2016

Figure 32. CRUSER Technical Continuum (TechCon), July 2016

NPS CRUSER held its fifth annual Technical Continuum (TechCon) on 12 and 13 July 2016. This event was for NPS students and faculty interested in education, experimentation and research related to employing unmanned systems in operational environments.

			TUESDAY 12 JULY
900	**905**	Dr. Ray Buettner: CRUSER Director	Welcome
905	**920**	C. Blais: NPS MOVES	Government-Owned Software for Robotics Education and Research
925	**940**	C. Blais: NPS MOVES	Challenges in Distinguishing Manned from Unmanned Systems in Combat Models
945	**1000**	R. Gamache: NPS PH	Electric Gun System
1005	**1020**	E. Gyde: BATTELLE	Interactive 360 Video for Autonomous and Unmanned Platforms
1025	**1040**	J. Reeder: SSC	Path Integral Control with Evolved Cost Functions for Control of Agile UAV Swarms
1045	**1100**	K. Song: NPS OC	Prototype Basic MCM UUV Search Mission Management AI Module Integration
1105	**1120**	D. Brutzman/D. Davis/C. Blais/R. McGhee: NPS MOVES	Ethical Mission Tasking and Execution for Maritime Robotic Vehicles
1125	**1140**	D. Mortimore: NUWC Keyport	Unmanned Systems Research and Experimentation Opportunities
1145	**1200**	H. Park/Tavora Romano/Yun:NPS MAE/ECE	Project MANICOPTER: Autonomous Aerial Vehicles with Robotic Manipulation Capability
1205	**1220**	J. Virgili-Llop/M. Romano: NPS MAE	Modeling and Control of UxV with Onboard Robotic Manipulators of Similar Size
1225	**1240**	K. Jones: NPS MAE	Aqua-Quad: Status and Future Developments
1245	**1300**	W. Kang: NPS MA	Observability and Optimal Sensor Placement for Mobile Sensor Networks
1305	**1320**	D. Boger/ S. Miller: NPS IS	Using Co-Active Design to Implement Marine Machine Interdependence in Squad Maneuvers
1325	**1340**	F. Alves: NPS PH	Bio-inspired MEMS Acoustic Sensor for Robotic Autonomous Systems Applications
1345	**1400**	S. Fahey: NPS CS	USV for Maritime Shield
1405	**1420**	S. Kragelund: NPS MAE	Experimentation in Extreme Environments: Recent Results by CAVR

			WEDNESDAY 13 JULY
900	**905**	Dr. Brian Bingham: CRUSER Deputy Director	Welcome
905	**920**	B. Bingham: NPS MAE	Developing Single Sortie Detect to Engage Multi-Vehicle Autonomy with Ground-Based Testbed
925	**940**	J. Joseph: NPS OC	Acoustic Characterization of the New Arctic using Unmanned Systems in ICEX-16
945	**1000**	Y. Kwon/J. Klamo: NPS SE/MAE	Unsteady Loads on UUV during Near Surface Operation
1005	**1020**	P. Thulasiraman: NPS ECE	Evaluation of Security Algorithms in Cyber Defense of UAV Swarm Communications
1025	**1040**	G. Xie: NPS CS	Reliable Ad-hoc Communication through Multi-path Data Delivery
1045	**1100**	D. Brutzman: NPS IS/USW	RoboData Archive for JIFX/CRUSER Unmanned System Experimentation
1105	**1120**	J. Testa/V. Dobrokhodov: NPS MAE	Vision-Based Relative Navigation of Multicopter UAV in Maritime Interdiction Operation
1125	**1140**	X. Yun/ J. Calusdian: NPS ECE	MATLAB Interface for the P3-DX Mobile Robot
1145	**1200**	C. Walton/ I. Kaminer: NPS MAE	Optimal Sensor Deployment and Information Gathering using UxSs
1205	**1220**	J. Metcalf/R.C. Olsen: NPS PH	Photogrammetric Point Cloud Fusion Using UAV Collected Thermal Imagery
1225	**1240**	R. Buettner/M. Jones: NPS IS	Swarm versus Swarm: Progress and Future Plans
1245	**1300**	K. Giammarco/M. Auguston/K. Giles: NPS SE/CS	Monterey Phoenix Behavior Modeling of Robotics and Unmanned Systems
1305	**1320**	P. Guest: NPS MR	Using Quad-rotor UAS to Perform Meteorological Measurements From Ships
1325	**1340**	S. Sanchez: NPS OR	Closing Capability Gaps: Data Farming Methods for New Concept Exploration in the CRUSER Community
1345	**1400**	S. Kragelund/ C. Walton/ I. Kaminer: NPS MAE	Sonar Detection Mission Planning Tool for Autonomous Vehicle Teams
1405	**1420**	D. Brutzman: NPS IS/USW	QR and DFL Optical Communications for Network Optional Warfare (NOW)

TechCon 2016 was intended to further concepts developed during the September 2015 Warfare Innovation Workshop, and showcase NPS student and faculty work in advancing unmanned systems. TechCon 2016 was held in a tent out on the academic quad. Presentations covered on-going student and faculty research, as well as proposals for CRUSER FY17 funding in research related to unmanned systems. The NPS CRUSER TechCon 2016 was unclassified, and live streamed by video for the non-resident CRUSER Community of Interest.

D. OUTREACH AND RELATIONSHIPS

1. Community of Interest

CRUSER continued to grow its membership throughout FY16. At the end of FY11, CRUSER's first program year, the CRUSER community of interest had grown to include almost 400 members. As of March 2014 this fledgling community consisted of over 1,300 members (*see Figure 33*). In the two years spanning 2012-2014 CRUSER more than doubled in size, from just of 800 members in September 2012 to approximately 1630 members as of September 2014. This is largely due to CRUSER web presence and member interaction with military, academic and industry personnel during field experimentation, workshops, educational for and CRUSER monthly meetings. FY15 brought the community over the 2,000 member mark and as of the end of FY16 on 30 September 2016 membership is just over 3,000. The following graphic depicts this continued steady rise in CRUSER membership.

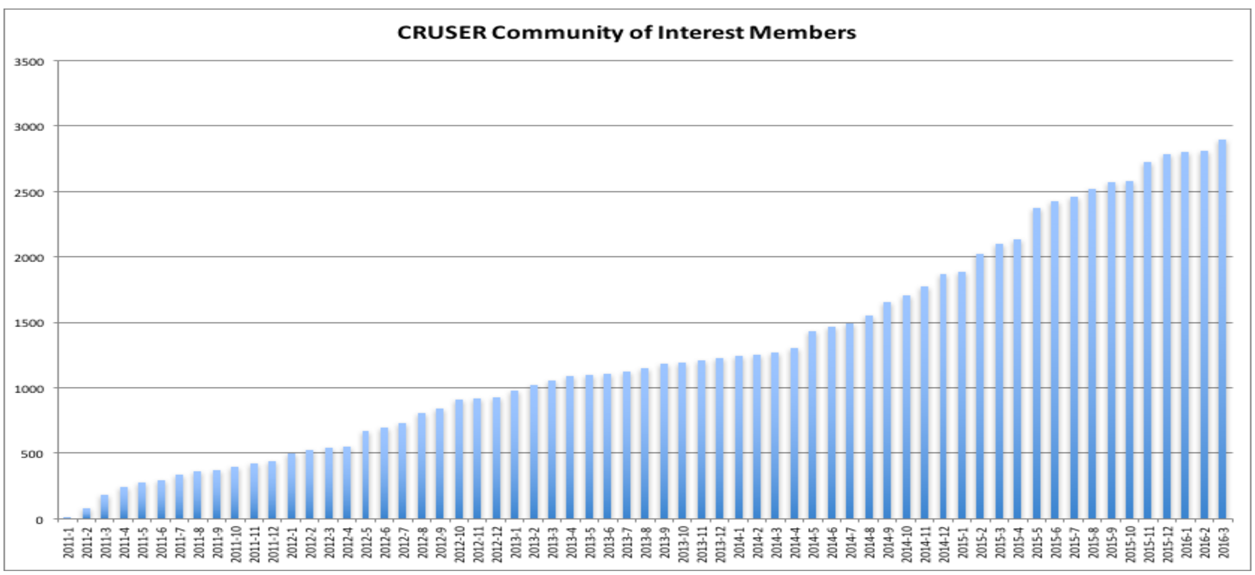


Figure 33. CRUSER community of interest growth from January 2011 to March 2016.

Beyond NPS community members, the CRUSER community of interest includes major stakeholders from across the DoD, as well as significant representation from industry and academia (*see Figure 34*).

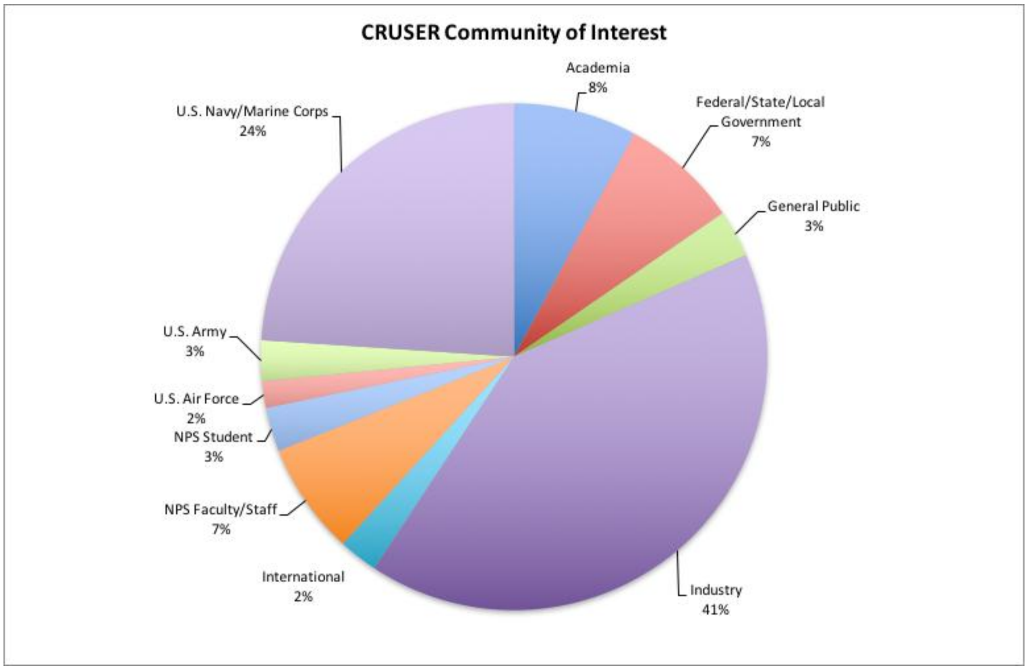


Figure 34. CRUSER community of interest breadth of membership (March 2016)

CRUSER continues to produce a periodic newsletter, and accepts article submissions from the entire community. This short document (4-6 pages) is made available electronically each quarter to the entire community distribution list. Additionally, CRUSER holds a monthly community meeting on the NPS campus. Non-resident members may join the meeting by phone, video, or using the campus distance learning tool Collaborate.

2. Briefings and Presentations

Over the six years of CRUSER operations the CRUSER leadership team has become regarded experts in unmanned systems and robotic and autonomous system developments resulting in a high demand for briefings, formal presentations and informal discussions. These activities are an important part of the CRUSER educational effort, both providing for an exchange of information that educates all parties involved. This is a sampling of those that received CRUSER briefings in FY16:

Table 7. FY16 CRUSER program briefings and presentations

DATE	ORGANIZATION
OCT 2015	Mr. Tom Reynolds, Hydroid Mr. Rafael Rodriquez, Naval Surface Warfare Center, Panama City RDML Tom Wears USN (ret), Northrop Grumman

	CSDS-12 TAG
NOV 2015	CAPT Glenn Allen, PMS 408 Mr. Eddie Cabrera, NASA JPL Navy Programs Dr. Erica Briscoe, Georgia Tech Research Institute (GTRI)
DEC 2015	Boeing Defense, United Kingdom
JAN 2016	Dr. Maura Sullivan, Chief Innovation and Strategy Officer, DoN National Homeland Security Consortium Annual Meeting (formal presentation, off campus) Joint Robotics and Autonomous Systems Working Group (formal presentation, off campus) Mark Gorenflo, Operations Officer, Defense Innovation Unit - x James Baker, Director, Office of Net Assessment, OSD
FEB 2016	BG Chris Burns, Assistant Commanding General, Special Operations Command - Central Command GEN David Perkins, Commanding General, US Army Training and Doctrine Command Dr. Richard Danzig, former Secretary of the Navy USMC Manned Unmanned Machine Teaming workshop (*formal presentation, off campus*)
MAR 2016	CHLSD Course Presentation (formal presentation, on campus) COL Ben Maitre, 27th SO Wing Commander, USAF 14th Ethics and Responsible Business Forum, The Ethics of Artificial Intelligence: The End of Humanity As We Know It?, CSUMB, (*formal presentation, off campus*)
APR 2016	The Military Conflict Institute (TMCI) Leadership Meeting, (*formal presentation, on campus*) Glenn Fogg, Deputy Director, Prototyping & Experimentation, OSD

	Dr. Brenda Oppermann, Consultant for Director of the Navy Staff Dr. Eui Lee, Deputy NAWCAD, NAVAIR Bill Glenney, CNO's Strategic Studies Group Navy Information Professional Annual Forum, Autonomous Systems and the Implications for C2 (*formal presentation, on campus*)
MAY 2016	International Defense Attaché Tour Dr. Paul Wolpe, Center for Bioethics, University of Pennsylvania International Mine Warfare Symposium Technical Session - Swarming Robotics (*formal presentation, off campus*) International Mine Warfare Symposium Plenary Session - Unmanned Systems Culture (*formal presentation, off campus*)
JUN 2016	UxS Roadmap Working Group - OSD, (*formal presentation, off campus*) ADM John Richardson, Chief of Naval Operations Cyber Endeavor - Planes, Trains, and Automobile (and Ships) panel (*formal presentation - on campus*) Hack the Sky - Swarm Challenge presentation and judging of results Dr. Janine Davidson, Under Secretary of the Navy RDML Boxall, OPNAV N96
JUL 2016	Hacking 4 Defense, RAS Domain Expert supporting UCSD effort at request of Under Secretary's office T.X Hammes, Institute for National Strategic Studies, National Defense University Jill Morrissett, Chief Scientist, Joint Warfare Analysis Center DASN (Unmanned)/OPNAV N99 Unmanned Workshop (attendee)

	Submarine Warfare Operations Research Division, Office of Naval Intelligence
AUG 2016	Undersea Warfighting Development Center (UWDC) Tactical Analysis Group G. Moss, Science Advisor to Commander, Submarine Force Pacific Fleet Thomas Hicks, DUSN, Management (r*oundtable participant*)
SEP 2016	LTG Kenneth Tovo, Commanding General, USA Special Operations Command Unmanned Systems Futures Workshop (*moderator and Master of Ceremonies*) Franklin Parker, ASN (Manpower and Reserve Affairs) VADM Mike Connor (USN-retired). ThayerMahan Inc.

3. 6th Annual Robots in the Roses Research Fair, April 2016

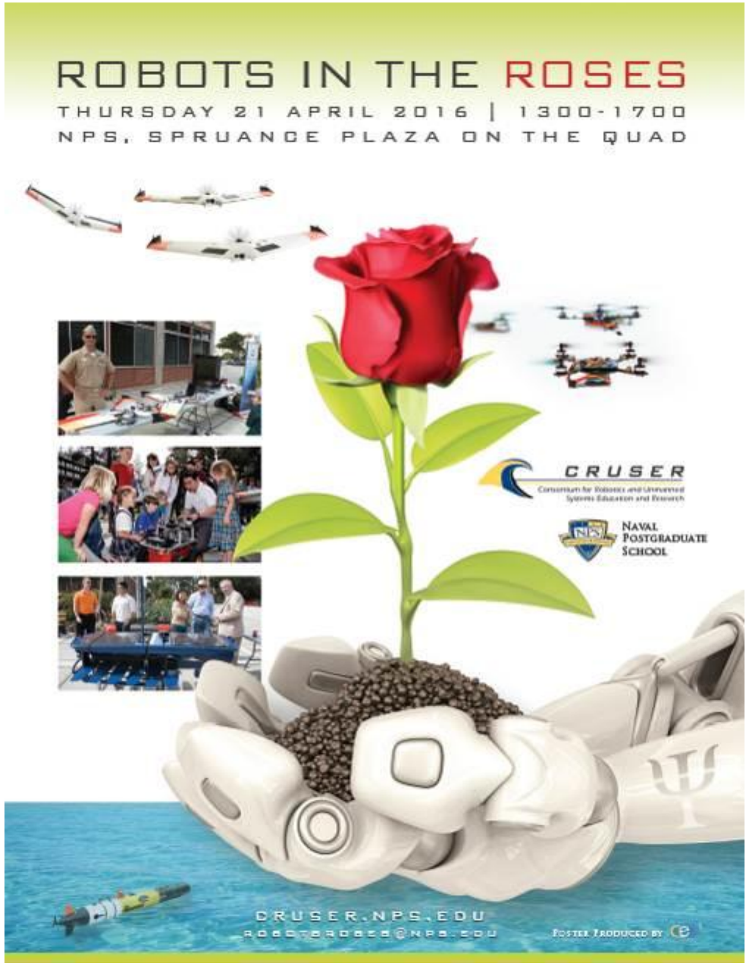


Figure 35. Robots in the Roses Research Fair, April 2016

Since 2011, CRUSER has hosted an annual research fair highlighting unmanned systems activity on the NPS campus. The invitation to this event was distributed to the NPS campus CRUSER community of interest to provide NPS students the opportunity to explore potential thesis topics involving emergent technology, and inspire younger students to approach their formal education in science, technology, engineering and math with zeal. Several hundred NPS staff, faculty, and students were joined by local community members and families on the NPS campus in Monterey.

4. CRUSER Expo

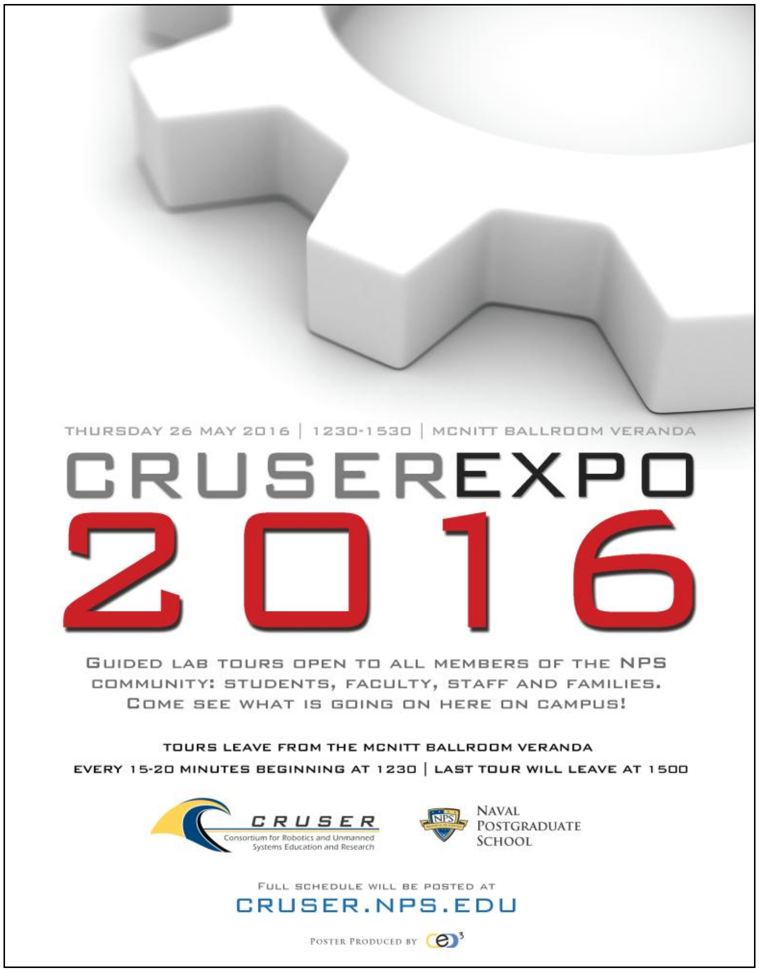


Figure 36. CRUSER Expo 2016, a series of guided lab tours, took place on 26 May 2016.

In conjunction with the International Mine Warfare Symposium, CRUSER Expo 2016 was a series of guided lab tours to showcase work by NPS CRUSER community members. Six guides led seven full tours through seven campus labs. Tour groups were made up of campus guests, NPS faculty and staff, and NPS students and their families. Some campus community members commented that although they had worked on campus for many years this was the first time they had the opportunity to observe the work they were supporting.

5. USN Reserve Relationships

CRUSER has an ongoing relationship with two distinct reserve components - The Office of Naval Research – Reserve Component (ONR-RC), and the Strategic Sealift Office (SSO) Reserve Program. ONR-RC continued to provide operational support to many CRUSER projects, programs, and events in FY16. Collaboration between CRUSER researchers at the Naval Postgraduate School (NPS) and ONR-RC began four years ago with personnel from the

ONR-113 unit, and has expanded to several additional ONR Reserve units. This is an extremely valuable relationship for CRUSER and the larger community of interest.

The SSO Reserve program evolved from the Maritime Administration (MARAD) Reserve program, and started their relationship with NPS through the Littoral Operations Center (LOC) to support the several iterations of the maritime security curriculum. As the campus liaison for the SSO reservists is also a member of the CRUSER leadership team, the SSO reservists have also been employed to support CRUSER and JIFX activities as they complete their annual duty training (ADT) at NPS. With a merchant mariner perspective, and many with recent operational experience, these reservists are quite valuable assets.

III. CONCLUSION

FY16 was the third year that CRUSER was at full funding and the year demonstrated the value of a broad based, multi-institutional consortium to the naval enterprise. CRUSERs growing reputation and impact led to the community growing beyond 3000 members, illustrating the value to the community of CRUSER's aligning effort.

CRUSER supported 22 individual theses and four group capstone projects in FY16. An additional eight theses were supported in September 2015 that were not included in the final count for the FY15 report as they were not yet processed when the report was released. Support to individual professors provided direct impact on teaching in NPS classrooms. CRUSER supported classroom projects designed provide input for larger naval wargames as well as providing direct feedback to operators and engineers in the fleet and at warfare centers. Discussions on the education options available within the greater Naval Enterprise to prepare future warfighters to incorporate robotics and autonomous systems began exploration of what curriculum may need to be developed to meet this growing need. CRUSER members are on innovation teams and advisory boards across the naval and defense enterprise. CRUSER also continues to play an important advisory role, with CRUSER leadership conducting reviews and providing input, by request, to the Joint Staff, Deputy Secretary of Defense and Under Secretary of the Navy during FY17.

A. PROPOSED FY17 ACTIVITIES

Finally, in FY17 the fifth CRUSER Innovation Thread will close out, work along the sixth thread will continue, and work will begin on the seventh thread. Proposed activities in FY17 include:

- As in past years, CRUSER will continue to fund the integration of robotics and unmanned systems issues into appropriate courses and support development of educational materials that will enable the Navy and Marine Corps officers afloat to become familiar with the challenges associated with the development and operational employment of these systems.

- CRUSER will host a sixth NPS CRUSER Technical Continuum (TechCon) to demonstrate technologies to explore development of the concepts generated the fall concept generation workshops, as well as to provide funded researchers an opportunity to share their findings.

- CRUSER will sponsor experimentation of the most promising technologies presented CRUSER TechCon 2016.

- CRUSER will explore all opportunities to share the results of completed Innovation Threads with sponsors.

- CRUSER will continue to support summer internships from the service academy students to work in labs across NPS throughout FY17.

- CRUSER will fund NPS student trips in FY17 to participate in research and experimentation dealing with all aspects of unmanned systems.

- CRUSER will complete FY17 with a concept generation workshop during NPS Thesis & Research Week on the academic calendar for 18-21 September 2017.

- CRUSER will continue Community of Interest database generation, newsletter production and distribution, and monthly community-wide meetings.

- CRUSER will continue development of a strategy for graduate and non-graduate education across the naval enterprise with regards to robotic and unmanned systems.

B. LONG TERM PLANS

In FY17 CRUSER will continue to support research and development with an emphasis on seeding new concepts, to include those developed in the annual concept generation workshops. As a program, CRUSER is likely to remain at full functioning strength for at least the next five years, and will continue to seek opportunities to connect communities and align disparate efforts developing robotics and autonomous systems across stakeholder groups.

APPENDIX A: PRESENTATIONS, PUBLICATIONS AND TECHNICAL REPORTS BY NPS CRUSER MEMBERS, FY11 TO PRESENT

This cumulative list of publications and scholarly presentations is representative of those completed by NPS CRUSER members since program launch in 2011. It is not meant to be all-inclusive, only give a sense of the depth and breadth of the impact of NPS CRUSER members in the academic community.

Added in FY16 report:

Boucher, R., W. Kang and Q. Gong (2016). “Galerkin Optimal Control” *Journal of Optimization Theory and Applications*, online DOI 10.1007/s10957-016-0918-x, 21 March 2016. Vol. 169, No. 3, pp 825 – 847.

Dobrokhodov, V. and K. Jones, C. Dillard, I. Kaminer (2016). "AquaQuad - Solar Powered, Long Endurance, Hybrid Mobil Vehicle for Persistent Surface and Underwater Reconnaissance, Part II - Onboard Intelligence," for *OCEANS 2016 MTS/IEEE* Monterey, 2016, Sep. 2016

Giammarco, K., Spencer Hunt, Clifford A. Whitcomb (2015). "An instructional design reference mission for search and rescue operations.” *NPS Technical Report* (NPS-SE-15-002). Monterey, CA, September 2015.

Guest, P. S., O. Persson, B. Blomquist, C. Fairall (2016). “Quantifying the impact of background atmospheric stability on air-ice-ocean interactions in the Arctic Ocean during fall freeze-up” a poster presented at the *AGU Ocean Sciences Conference*, New Orleans, LA, February 21-26, 2016.

Jones, K. and V. Dobrokhodov (2016). “Hybrid Mobile Buoy for Persistent Surface and Underwater Exploration,” *U.S. Patent 9,321,529* filed April 7th, 2014, and issued April 8th, 2016.

Jones, K. and V. Dobrokhodov (2016). “Multirotor Mobile Buoy for Persistent Surface and Underwater Exploration,” *U.S. Patent 9,457,900 B1* filed March 18th, 2016, and issued October 4th, 2016.

Jones, K. and V. Dobrokhodov, C. Dillard (2016). “Aqua-Quad - Solar Powered, Long Endurance, Hybrid Mobile Vehicle for Persistent Surface and Underwater Reconnaissance, Part I - Platform Design” proceedings of *2016 MTS/IEEE OCEANS’16*, Monterey, CA September 2016.

Jones, K. and V. Dobrokhodov, C. Dillard, I. Kaminer (2016). “Aqua-Quad - Solar Powered, Long Endurance, Hybrid Mobile Vehicle for Persistent Surface and Underwater Reconnaissance, Part II – Onboard Intelligence” proceedings of *2016 MTS/IEEE OCEANS’16*, Monterey, CA September 2016.

Kang, Wei and Lucas Wilcox (2015). An Example of Solving HJB Equations Using Sparse Grid for Feedback Control, *Proceedings of IEEE Conference on Decision and Control*, Osaka, Japan, December 15-18, 2015.

Kang, Wei (2015). Mitigating the Curse of Dimensionality: Sparse Grid Characteristics Method for Optimal Feedback Control and HJB Equations, arXiv:1507.04769v2, Nov. 16, 2015.

Kline, J. (2016). “Impacts of the Robotics Age on Naval Force Structure Planning,” *Naval War College EMC Chair Symposium on Maritime Strategy* presentation and working paper, 23 March 2016.

Kolsch, M., J. Li, Dong Hye Ye, T.H. Chung, J. Wachs, C. Bouman (2016). “Multi-Target Detection and Tracking from a Single Camera in Unmanned Aerial Vehicles (UAVs)” presented at *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 9-14 October 2016, Daejeon, Korea

Kragelund, S., C. Walton, I. Kaminer, “Sensor-based motion planning for autonomous vehicle teams,” in Oceans - Monterey, 2016, Sep. 2016. *Paper presented at OCEANS 2016 MTS/IEEE Monterey on September 21, 2016 and scheduled for publication in ISBN 978-1-5090-1527-6 (IEEE Catalog Number CFP16OCE-POD)*

Thomson, J. , P. S. Guest (et al) (2016). “Emerging trends in the seas state of the Beaufort and Chukchi seas” *Ocean Modelling*, V 105, September 2016.

Thompson, R.B. and P. Thulasiraman (2016). “Confidential and Authenticated Communications in a Large Fixed-Wing UAV Swarm,” in Proc. of *IEEE 15th International Symposium on Network Computing and Applications*, pp. 375-382, November 2016.

Vio, R. P. and R. Cristi, K. B. Smith (2016). “Near real-time improved UUV positioning through channel estimation – The Unscented Kalman Filter Approach” for *OCEANS 2016 MTS/IEEE* Monterey CA September 2016.

Walton, C. and C. Phelps, Qi Gong, I. Kaminer (2016). "A Numerical Algorithm for OptimalControl of Systems with Parameter Uncertainty, *10th IFAC NOLCOS Conference*, Monterey, August 2016

Walton, C. and S. Kragelund, I. Kaminer (2016). The Application of ‘Optimal Search’ to Marine Mapping," for *OCEANS 2016 MTS/IEEE* Monterey, 2016, Sep. 2016

Yakimenko, O. (2016). “UAVs and How They Work Together with Satellite Systems” presentation for *Singapore Space Challenge* 2016, 24 June 2016.

Included in FY15 report:

Andersson, K., I. Kaminer, V. Dobrokhodov, and V. Cichella (2012). "Thermal Centering Control for Autonomous Soaring; Stability Analysis and Flight Test Results," *Journal of Guidance, Control, and Dynamics*, Vol. 35, No. 3 (2012), pp. 963-975. doi: 10.2514/1.51691

Auguston, M. and C. Whitcomb (2012). "Behavior Models and Composition for Software and Systems Architecture", *ICSSEA 2012, 24th International Conference on SOFTWARE & SYSTEMS ENGINEERING and their APPLICATIONS*, Telecom ParisTech, Paris, 23-25 October 2012. http://icssea.enst.fr/icssea12/

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Auguston, Mikhail, Kristin Giammarco, W. Clifton Baldwin, Ji’on Crump, and Monica Farah-Stapleton (2015). Modeling and verifying business processes with Monterey Phoenix. Procedia Computer Science issue 44: Pages 345-353.

Boxerbaum, A., M. Klein, J. Kline, S. Burgess, R. Quinn, R. Harkins, R. Vaidyanatham (2012). "Design, Simulation, Fabrication and Testing of Bio-Inspired Amphibious Robot with Multiple Modes of Mobility," *Journal of Robotics and Mechatronics*, Vol. 24, No.4 August 2012.

Boucher, R., W. Kang, and Q. Gong (2014). Galerkin Optimal Control for Constrained Nonlinear Problems, *American Control Conference*, Portland, OR, June 2014.

Boucher, R., W. Kang, and Q. Gong, Discontinuous Galerkin Optimal Control for Constrained Nonlinear Problems, *IEEE ICCA*, Taichung, Taiwan, June 2014.

Brutzman, D., with T. Chung, C. O’Neal, J. Ellis and L. Englehorn (2011). *Future Unmanned Naval Systems (FUNS) Wargame Competition Final Report* (NPS-USW-2011-001) released July 2011.

Carpin, S., Chung, T. H., & Sadler, B. M. (2013). Theoretical Foundations of High-Speed Robot Team Deployment. In *Proceedings of the 2013 IEEE International Conference on Robotics and Automation*.

Chitre, M. (2012). “What is the impact of propagation delay on network throughput?” *Proc.NATO Underwater Communications Conf. (UComms)*, Sestri Levante, Italy, Sept 12-14, 2012

Chitre, M., A. Mahmood, and M. Armand (2012). “Coherent communications in snapping-shrimp dominated ambient noise environments,” *Proc. Acoustics 2012* Hong Kong, vol. 131, p. 3277, May 2012

Chitre, M. (2013). “Teamwork among marine robots - advances and challenges,” *Proc. WMR2013 - Workshop on Marine Robotics*, Las Palmas de Gran Canaria, Spain, February 2013

Chitre, M., I. Topor, R. Bhatnagar and V. Pallayil (2013). “Variability in link performance of an underwater acoustic network,” *Proc. IEEE Oceans Conf*., Bergen, Norway, June 2013

Chung, T. H., Jones, K. D., Day, M. A., Jones, M., and Clement, M. R. (2013). 50 VS. 50 by 2015: Swarm Vs. Swarm UAV Live-Fly Competition at the Naval Postgraduate School. In *AUVSI North America*. Washington, D.C.

Cichella, Choe, Mehdi, Xargay, Hovakimyan, Kaminer, Dobrokhodov, Pascoal, and Aguiar (2014).“Safe Time-Critical Cooperative Missions for Multiple Multirotor UAVs,” Robotics Science and Systems. Workshop on *Distributed Control and Estimation for Robotic Vehicle Networks*, Berkeley, CA, July 2014.

Cichella, Choe, Mehdi, Xargay, Hovakimyan, Trujillo, and Kaminer (2014). “Trajectory Generation and Collision Avoidance for Time-Coordination of UAVs,” *AIAA Guidance, Navigation, and Control Conference*, National Harbour, MD, January 2014.

Day, Michael A. et al. (2015). “Multi-UAV Software Systems and Simulation Architecture". In: *2015 International Conference on Unmanned Aerial Systems*. Denver, CO: IEEE, 2015, pp. 426-435.

Dono, T., and Chung, T. H. (2013). Optimized Transit Planning and Landing of Aerial Robotic Swarms. In *Proc. of 2013 IEEE Int’l. Conf. on Robotics and Automation*.

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Du Toit, N.E. (2015). “Putting AUVs to Work: Enabling Close-Proximity AUV Operations” MBARI Seminar Series, Moss Landing, August 2015

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Dulo, D. (2013). Panel Member/Speaker. *Drones Incoming! Are you Ready for Unmanned Aerial Vehicles?* American Bar Association Annual Meeting August 2013, Chicago, IL. http://www.americanbar.org/news/abanews/aba-news-archives/2015/08/drone_regulationsde.html

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E. Capello, H. Park, B. Tavora, G. Gugleri, and M. Romano (2015). "Modeling and Experimental Parameter Identification of a Multicopter via a Compound Pendulum Test Rig." 2015 International Workshop on Research, Education, and Development on Unmanned Aerial Systems (RED-UAS 2015) *submitted.*

Economist (2013). "Underwater Networking: Captain Nemo goes online," *The Economist Magazine*, March 9, 2013

Ellis, W., D. McLay and L. Englehorn (2013). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Warfare Innovation Workshop (WIW) 2013 After Action Report: Undersea Superiority 2050,* released May 2013.

Gagnon, P. and J, Rice, G. Clark (2012). "Channel Modeling and Time Delay Estimation for Clock Synchronization Among Seaweb Nodes," *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012

Gagnon, P. and J. Rice, G. A. Clark, "Clock Synchronization through Time-Variant Underwater Acoustic Channels," *Proc. NATO Underwater Communications Conference (UComms)*, Sestri Levante, Italy, 12-14 September 2012

Gardner, Maxine, LCDR, U.S. Navy (2014). "The Navy's Role in Humanitarian Assistance," *CRUSER TechCon 2014*, Monterey, California, April 2014.

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Guest, Peter S. (2014). The Use of Unmanned Systems for Environmental Sampling and Enhanced Battlespace Awareness in Support of Naval Operations, *CRUSER News*, Published at the Naval Postgraduate School, Monterey CA, January 2014.

Guest, Peter S. (2014).Using UAS to Sense the Physical Environment, presented at the *NPS OPNAV N2/N6 Studies Fair Potential Theses Topics*, Naval Postgraduate School, Monterey CA, 9 January 2014

Guest, Peter S. (2014). Atmospheric Measurements From a Mini-Quad Rotor UAV – How Accurate Are Measurements Near the Surface? *CRUSER TechCon 2014*, Monterey CA, 9 April 2014.

Guest, Peter S. (2014). How accurate are measurements near the surface? A poster presented at the *CRUSER 4th Annual "Robots in the Roses" Research Fair*, Naval Postgraduate School, Monterey CA, 10 April 2014.

Guest Peter S. (2014). Using Miniature Multi-Rotor Unmanned Aerial Vehicles for Performing Low Level Atmospheric Measurements, presented at *the 94th American Meteorological Society Annual Meeting, 18th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS) Session 8: Field Experiments*, Atlanta Georgia, 5 August 2014.

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Guest, Peter S. (2013). "Using small unmanned aerial vehicles for undersea warfare," presented at the *NPS CRUSER Technical Continuum*, 9 April 2013.

Guest, Peter S., Paul Frederickson, Arlene Guest and Tom Murphree (2013). "Atmospheric measurements with a small quad-rotor UAV," a poster presented at the *"Robots in the Roses" Research Fair*, 11 April, 2013.

Guest Peter S. (2013). "The use of kites, tethered balloons and miniature unmanned aerial vehicles for performing low level atmospheric measurements over water, land and sea ice surfaces," abstract accepted for presentation at the *94th American Meteorological Society Annual Meeting, 18th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*, submitted 15 August, 2013.

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Guest, Peter S., Trident Warrior 2013 (2013). "Evaporation and surface ducts," presented at the *Trident Warrior 2013 Meeting, Naval Research Laboratory*, Monterey CA, 23 September, 2013.

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Guest, Peter S. and Christopher R. Machado (2014). “Using UAS to sense the physical environment and predict electromagnetic system performance.” *Naval Postgraduate School Technical Report* NPS-MR-15-001, Monterey CA, November 2014.

Hermsdorfer, Kate, Qing Wang, Richard Lind, Ryan Yamaguchi, and John Kalogiros (2015). “Autonomous Wave Gliders for Air-sea Interaction Research.” *19th Conference on Air-Sea Interaction*, 4–8 January 2015, Phoenix, Arizona

Kaminer, I. (2014). "Maritime Force Protection and Herding," Presented at *ONR Science of Autonomy Workshop*, DC August 2014

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APPENDIX B: CUMULATIVE THESES AND STUDENT PROJECTS SUPPORTED

This list includes thesis and projects from FY11 forward. Unclassified NPS theses are available through the NPS Dudley Knox Library and DTIC. This list is alphabetized by student last name, and separated by year of completion (chronologically backward). As of September 2015, CRUSER has supported nearly 200 master's theses and capstone projects, and one doctoral dissertation.

Added in this report for FY16:

AUTHOR(s)	TITLE	DATE (year-mo)	URL
Sean X. Hong	Phased array excitations for efficient near field wireless power transmission	2016-09	
LT David Armandt USN	Controlling robotic swarm behavior utilizing real-time kinematics and artificial physics	2016-06	http://hdl.handle.net/10945/49465
ENS Eric B. Bermudez USN	Terminal homing for autonomous underwater vehicle docking	2016-06	http://hdl.handle.net/10945/49385
Capt. Jerry V. Drew II USA	Evolved design, integration, and test of a modular, multi-link, spacecraft-based robotic manipulator	2016-06	http://hdl.handle.net/10945/49446
LTJG Alejandro Garcia Aguilar Mexican Navy	CFD analysis of the SBXC Glider airframe	2016-06	http://hdl.handle.net/10945/49466
CMDR Andrew B. Hall USN	Conceptual and preliminary design of a low-cost precision aerial delivery system	2016-06	http://hdl.handle.net/10945/49478
LTJG Serif Kaya Turkish Navy	Evaluating effectiveness of a frigate in an anti-air warfare (AAW) environment	2016-06	http://hdl.handle.net/10945/49504
SEA 23 Cohort	Unmanned systems in integrating cross-domain naval fires	2016-06	http://hdl.handle.net/10945/49381
Capt. Matthew S. Zach USMC	Unmanned tactical autonomous control and collaboration coactive design	2016-06	http://hdl.handle.net/10945/49417

LCDR Jose R. Espinosa Gloria Mexican Navy	Runway detection from map, video and aircraft navigational data	2016-03	http://hdl.handle.net/10945/48516
LT Matthew S. Maupin USN	Fighting the network: MANET management in support of littoral operations	2016-03	http://hdl.handle.net/10945/48561
LCDR Brian M. Roth USN and LCDR Jade L. Buckler USN	Unmanned Tactical Autonomous Control and Collaboration (UTACC) unmanned aerial vehicle analysis of alternatives	2016-03	http://hdl.handle.net/10945/48586
LT Manuel Ariza Colombian Navy	The design and implementation of a prototype surf-zone robot for waterborne operations	2015-12	http://hdl.handle.net/10945/47847
LT Loney R. Cason III USN	Continuous acoustic sensing with an unmanned aerial vehicle system for anti-submarine warfare in a high-threat area	2015-12	http://hdl.handle.net/10945/47918
LT Ross A. Eldred USN	Autonomous underwater vehicle architecture synthesis for shipwreck interior exploration	2015-12	http://hdl.handle.net/10945/47940
LT Robert T. Fauci III USN	Power management system design for solar-powered UAS	2015-12	http://hdl.handle.net/10945/47942
LCDR Oscar García Chilean Navy	Sensors and algorithms for an unmanned surf-zone robot	2015-12	http://hdl.handle.net/10945/47949
SE Team Mental Focus	A decision support system for evaluating systems of undersea sensors and weapons	2015-12	http://hdl.handle.net/10945/47868
SE Team Mine Warfare 2015	Scenario-based systems engineering application to mine warfare	2015-12	http://hdl.handle.net/10945/47865
SE Team TECHMAN	Systems engineering of unmanned DoD systems: following the Joint Capabilities Integration and Development System/Defense Acquisition System process to develop an unmanned ground vehicle system	2015-12	http://hdl.handle.net/10945/47867

Added in FY15:

AUTHOR(s)	TITLE	DATE (year-mo)	URL

Capt. Robert Humeur Swedish Army	A New High-Resolution Direction Finding Architecture Using Photonics and Neural Network Signal Processing for Miniature Air Vehicle Applications	2015-09	http://hdl.handle.net/10945/47276
LT Spencer S. Hunt, USN	Model based systems engineering in the execution of search and rescue operations.	2015-09	http://hdl.handle.net/10945/47277
Capt Caroline A. Scudder, USMC	Electronic Warfare Network Latency Within SUAS Swarms	2015-09	
LT Sean M. Sharp, USN	Impact of Time-Varying Sound Speed Profiles with Seaglider on ASW Detection Ranges in the Strait of Hormuz (SECRET).	2015-09	
Victoria Steward	Functional flow and event-driven methods for predicting system performance.	2015-09	http://hdl.handle.net/10945/47334
Maj Thomas M. Rice, USMC Maj Erik A. Keim, USMC Maj Tom Chhabra, USMC	Unmanned Tactical Autonomous Control and Collaboration Concept of Operations	2015-09	http://hdl.handle.net/10945/47319
Capt Patrick N. Coffman, USMC	Capabilities assessment and employment recommendations for Full Motion Video Optical Navigation Exploitation (FMV-ONE)	2015-06	http://hdl.handle.net/10945/45827
LT David Cummings, USN	Survivability as a tool for evaluating open source software	2015-06	http://hdl.handle.net/10945/45833
Capt Louis T. Batson, USMC Capt Donald R. Wimmer, Jr., USMC	Unmanned Tactical Autonomous Control and Collaboration threat and vulnerability assessment	2015-06	http://hdl.handle.net/10945/45738
LT Arturo Jacinto, II, USN	Unmanned systems: a lab-based robotic arm for grasping	2015-06	http://hdl.handle.net/10945/45879
LTJG Salim Unlu, Turkish Navy	Effectiveness of unmanned surface vehicles in anti-submarine warfare with the goal of protecting a high value unit	2015-06	http://hdl.handle.net/10945/45955
Systems Engineering Analysis Capstone SEA21A	Organic over-the-horizon targeting for the 2025 surface fleet	2015-06	http://hdl.handle.net/10945/45933
LCDR Michael C. Albrecht, USN	Air asset to mission assignment for dynamic high-threat environments in real-time	2015-03	http://hdl.handle.net/10945/45155
LCDR Vincent H. Dova, USN	Software-defined avionics and mission systems in future vertical lift aircraft	2015-03	http://hdl.handle.net/10945/45181

LCDR Maxine J. Gardner, USN	Investigating the naval logistics role in humanitarian assistance activities	2015-03	http://hdl.handle.net/10945/45189
LT Bruce W. Hill, USN	Evaluation of efficient XML interchange (EXI) for large datasets and as an alternative to binary JSON encodings	2015-03	http://hdl.handle.net/10945/45196
LT Seneca R. Johns, USN	Automated support for rapid coordination of joint UUV operation	2015-03	http://hdl.handle.net/10945/45199
LT Forest B. Mclaughlin, USN	Undersea communications between submarines and unmanned undersea vehicles in a command and control denied environment	2015-03	http://hdl.handle.net/10945/45224
LT Adam R. Sinsel, USN	Supporting the maritime information dominance: optimizing tactical network for biometric data sharing in maritime interdiction operations	2015-03	http://hdl.handle.net/10945/45257
LT Andrew R. Thompson, USN	Evaluating the combined UUV efforts in a large-scale mine warfare environment	2015-03	http://hdl.handle.net/10945/45263
LT Bradley R. Turnbaugh, USN	Extending quad-rotor UAV autonomy with onboard image processing	2015-03	http://hdl.handle.net/10945/45265
LT Nicholas D. Vallardarez, USN	An adaptive approach for precise underwater vehicle control in combined robot-diver operations	2015-03	http://hdl.handle.net/10945/45268
Laser-Based Training Assessment Team, Cohort 311-133A	Research and analysis of possible solutions for Navy-simulated training technology	2015-03	http://hdl.handle.net/10945/45245
HEL Battle Damage Assessment Team, Cohort 311-133O	Increasing the kill effectiveness of High Energy Laser (HEL) Combat System	2015-03	http://hdl.handle.net/10945/45247
HEL Test Bed Team, Cohort 311-133O	Comprehensive system-based architecture for an integrated high energy laser test bed	2015-03	http://hdl.handle.net/10945/45246
LtCol Thomas A. Atkinson, USMC	Marine Corps expeditionary rifle platoon energy burden	2014-12	http://hdl.handle.net/10945/44514
LT Brenton Campbell, USN	Human robotic swarm interaction using an artificial physics approach	2014-12	http://hdl.handle.net/10945/44531
LT Chase H. Dillard, USN	Energy-efficient underwater surveillance by means of hybrid aquacopters	2014-12	http://hdl.handle.net/10945/44551
LCDR Kathryn M. Hermsdorfer, USN	Environmental data collection using autonomous Wave Gliders	2014-12	http://hdl.handle.net/10945/44577
LT Ryan P. Hilger, USN	Acoustic communications considerations for collaborative simultaneous localization and mapping	2014-12	http://hdl.handle.net/10945/44579
LCDR Ramon P. Martinez, USN	Bio-Optical and Hydrographic Characteristics of the western Pacific Ocean for Undersea Warfare Using Seaglider Data	2014-12	http://hdl.handle.net/10945/44612

LT Mark C. Mitchell, USN	Impacts of potential aircraft observations on forecasts of tropical cyclones over the western North Pacific	2014-12	http://hdl.handle.net/10945/44619
LT Dominic J. Simone, USN	Modeling a linear generator for energy harvesting applications	2014-12	http://hdl.handle.net/10945/44669
Team MIW, SE311-132Open/	Application of Model-Based Systems Engineering (MBSE) to compare legacy and future forces in Mine Warfare (MIW) missions		http://hdl.handle.net/10945/44659
Joong Yang Lee, NTU Singapore	Expanded kill chain analysis of manned-unmanned teaming for future strike operations	2014-09	http://hdl.handle.net/10945/43944
Montrell Smith, DON Civilian	Converting a manned LCU into an unmanned surface vehicle (USV): an open systems architecture (OSA) case study	2014-09	http://hdl.handle.net/10945/44004
CDR Ellen Chang, USNR	Defining the levels of adjustable autonomy: a means of improving resilience in an unmanned aerial system	2014-09	http://hdl.handle.net/10945/43887
Chee Siong Ong, NTU Singapore	Logistics supply of the distributed air wing	2014-09	http://hdl.handle.net/10945/43969
LT Barry Scott, USNR	Strategy in the robotic age: a case for autonomous warfare	2014-09	http://hdl.handle.net/10945/43995
LT Blake Wanier, USN	A modular simulation framework for assessing swarm search models	2014-09	http://hdl.handle.net/10945/44027
Chung Siong Tng, NTU Singapore	Effects of sensing capability on ground platform survivability during ground forces maneuver operations	2014-09	http://hdl.handle.net/10945/44018
LT Nicole R. Ramos, USN	Assessment of vision-based target detection and classification solutions using an indoor aerial robot	2014-09	http://hdl.handle.net/10945/43984
Ceying Foo, NTU Singapore	A systems engineering approach to allocate resources between protection and sensors for ground systems for offensive operations in an urban environment	2014-09	http://hdl.handle.net/10945/43914
Team Amberland, Cohort 311-131O	A systems approach to architecting a mission package for LCS support of amphibious operations	2014-09	http://hdl.handle.net/10945/43992

FY11-FY14:

Thesis project title/subject:	**NPS Student (s)**	
Applying Cooperative Localization to Swarm UAVs using an Extended Kalman Filter	Lieutenant Colonel Robert B. Davis, USMC	FY14 (SEP)
Expanded Kill Chain Analysis of Manned-Unmanned Teaming for Future	Joong Yang Lee, Republic of Singapore	FY14 (SEP)

Strike Operations	Air Force	
Logistics Supply of the Distributed Air Wing	Mr. Chee Siong Ong, Singapore Defence Science and Technology Agency	FY14 (SEP)
Assessment of Vision-Based Target Detection and Classification Solutions Using an Indoor Aerial Robot	LT Nicole Ramos, USN	FY14 (SEP)
Optimal Estimation of Glider's Underwater Trajectory with Depth-dependent Correction using the Regional Navy Coastal Ocean Model with Application to ASW	JooEon Shim	FY14 (SEP)
Relationship between the sonic layer depth and mixed layer depth identified from underwater glider with application to ASW	LT Vance Villarreal, USN	FY14 (SEP)
] A Modular Simulation Framework for Assessing Swarm Search Models	LT Blake Wanier, USN	FY14 (SEP)
The distributed air wing	Systems Engineering Analysis Cross-Campus Study (SEA 20B)	FY14
Sea-Shore interface robotic design	LT Timothy L. Bell, USN	FY14
Achieving information superiority using hastily formed networks and emerging technologies for the Royal Thai Armed Forces counterinsurgency operations in Southern Thailand	LCDR Anthony A. Bumatay, USN; LT Grant Graeber, USN	FY14
Droning on: American strategic myopia toward unmanned aerial systems	CWO4 Carlos S. Cabello, USA	FY14
Obstacle detection and avoidance on a mobile robotic platform using active depth sensing	ENS Taylor K. Calibo, USN	FY14
Improving operational effectiveness of Tactical Long Endurance Unmanned Aerial Systems (TALEUAS) by utilizing solar power	LT Nahum Camacho, Mexican Navy	FY14
Increasing the endurance and payload capacity of unmanned aerial vehicles with thin-film photovoltaics	Capt Seamus B. Carey, USMC	FY14
Power transfer efficiency of mutually coupled coils in an aluminum AUV hull	LCDR James M. Cena, USN	FY14
Tropical cyclone reconnaissance with the Global Hawk: operational thresholds and characteristics of convective systems over the tropical Western North Pacific	LCDR David W. Damron, USN	FY14
Cost-effectiveness analysis of aerial platforms and suitable communication payloads	LCDR Randall E. Everly, USN; LT David C. Limmer, USN	FY14
Characterization parameters for a three degree of freedom mobile robot	LT Jessica L. Fitzgerald, USN	FY14
Computer-aided detection of rapid, overt, airborne, reconnaissance data with the capability of removing oceanic noises	LT James R. Fritz, USN	FY14

A data-driven framework for rapid modeling of wireless communication channels (PhD dissertation)	Douglas Horner, NPS	FY14
An analysis of the defense acquisition strategy for unmanned systems	Maj Courtney David Jones, USMC	FY14
Terrain aided navigation for REMUS autonomous underwater vehicle	ENS Jacob T. Juriga, USN	FY14
Investigation of acoustic vector sensor data processing in the presence of highly variable bathymetry	LT Timothy D. Kubisak, USN	FY14
U.S. Army Unmanned Aircraft Systems (UAS)â€"a historical perspective to identifying and understanding stakeholder relationships	Donald R. Lowe, DON (Civ); Holly B. Story, DOA (Civ); Matthew B. Parsons, DOA (Civ)	FY14
Preliminary design of an autonomous underwater vehicle using multi-objective optimization	LCDR Sotirios Margonis, Hellenic Navy	FY14
Da Vinci's children take flight: unmanned aircraft systems in the homeland	Jeanie Moore, FEMA Office of External Affairs	FY14
A comparison of tactical leader decision making between automated and live counterparts in a virtual environment	MAJ Scott A. Patton, USA	FY14
High Energy Laser Employment in Self Defense Tactics on Naval Platforms [RESTRICTED]	LT Brett Robblee, USN	FY14
Optimal deployment of unmanned aerial vehicles for border surveillance	First LT Volkan Sözen, Turkish Army	FY14
Domestic aerial surveillance and homeland security: should Americans fear the eye in the sky?	LCDR Barcley W. Stamey, USN	FY14
Lightening the load of a USMC Rifle Platoon through robotics integration	LT Sian E. Stimpert, USN	FY14
Small Tactical Unmanned Aerial System (STUAS) Rapid Integration and fielding process (RAIN)	Christopher Ironhill, Bryan Otis, Frederick Lancaster, Angel Perez, Diana Ly, and Nam Tran	FY13 (SEP)
Development and validation of a controlled virtual environment for guidance, navigation and control of quadrotor UAV	Junwei Choon, Singapore Technologies Aerospace	FY13 (SEP)
An examination of the collateral psychological and political damage of drone warfare in the FATA region of Pakistan	Judson J. Dengler, U.S. Secret Service	FY13 (SEP)
Integrating Unmanned Aerial Vehicles into surveillance systems in complex maritime environments	LCDR Georgios Dimitriou, Hellenic Navy	FY13 (SEP)
Improving the Army's joint platform allocation tool (JPAT)	LT John P. Harrop, USN	FY13 (SEP)
Active shooters: is law enforcement ready for a Mumbai style attack?	Captain Joel M. Justice, Los Angeles Police Department	FY13 (SEP)

The rise of robots and the implications for military organizations	Captain Zhifeng Lim, Singapore Armed Forces	FY13 (SEP)
Dynamic bandwidth provisioning using Markov chain based on RSVP	Lieutanant Junior Grade Yavuz Sagir, Turkish Navy	FY13 (SEP)
Systems engineering and project management for product development: optimizing their working interfaces	Mariela I. Santiago, NUWC Newport	FY13 (SEP)
Dynamic towed array models and state estimation for underwater target tracking	LCDR Zachariah H. Stiles, USN	FY13 (SEP)
Diver relative UUV navigation for joint human-robot operations	LT Andrew T. Streenan, USN	FY13 (SEP)
Closing the gap between research and field applications for multi-UAV cooperative missions	Harn Chin Teo, ST Aerospace Ltd.	FY13 (SEP)
Enhancing entity level knowledge representation and environmental sensing in COMBATXXI using unmanned aircraft systems	MAJ James C. Teters,II, USA	FY13 (SEP)
Real-time dynamic model learning and adaptation for underwater vehicles	LT Joshua D. Weiss, USN	FY13 (SEP)
2024 Unmanned undersea warfare concept	Systems Engineering Analysis Cross-Campus Study (SEA 19A)	FY13
Mobility modeling and estimation for delay tolerant unmanned ground vehicle networks	LT Timothy M. Beach, USN	FY13
Effectiveness of Unmanned Aerial Vehicles in helping secure a border characterized by rough terrain and active terrorists	First Lieutenant Begum Y. Ozcan, Turkish Air Force	FY13
Integration Of Multiple Unmanned Systems In An Urban Search And Rescue Environment	Boon Heng Chua, Defence Science and Technology Agency, Singapore	FY13
Analysis of Ocean Variability in the South China Sea for Naval Operations	LT Mary Doty	FY13
Computer Aided Mine Detection Algorithm for Tactical Unmanned Aerial Vehicle (TUAV)	LT James Fritz	FY13
UAV swarm tactics: an agent-based simulation and Markov process analysis	Captain Uwe Gaertner, German Army	FY13
Extending the endurance of small unmanned aerial vehicles using advanced flexible solar cells	Capt Christopher R. Gromadski, USMC	FY13
The Optimal Employment and Defense of a Deep Seaweb Acoustic Network for Submarine Communications at Speed And Depth using a Defender-Attacker-Defender Model	LT Andrew Hendricksen, USN	FY13
Integrating Coordinated Path Following Algorithms To Mitigate The Loss Of Communication Among Multiple UAVs	LT Kyungnho Kim, USN	FY13

Intelligence fused Oceanography for ASW using Unmanned Underwater Vehicles (UUV)[SECRET]	LCDR Paul Kutia	FY13
Digital Semaphore: technical feasibility of QR code optical signaling for fleet communications	LCDR Andrew R. Lucas, USN *(thesis award winner)*	FY13
Effects Of UAV Supervisory Control On F-18 Formation Flight Performance In A Simulator Environment	LCDR Eric L. McMullen, USN and MAJ Brian Shane Grass, U.S. Army	FY13
Analysis of Bioluminescence and Optical Variability in the Arabian Gulf and Gulf of Oman for Naval Operations[Restricted]	LT Thai Phung	FY13
Digital semaphore: tactical implications of QR code optical signaling for fleet communications	LT Stephen P. Richter, USN *(thesis award winner)*	FY13
Design and hardware-in-the-loop implementation of optimal canonical maneuvers for an autonomous planetary aerial vehicle	LT Marta Savage, USN	FY13
Improving UXS network availability with asymmetric polarized mimo	Robert N. Severinghaus	FY13
Modeling and simulation for a surf zone robot	LT Eric Shuey, USN and LT Mika Shuey, USN	FY13
Analysis of Nondeterministic Search Patterns for Minimization of UAV Counter-Targeting	LT Timothy S. Stevens, USN	FY13
A human factors analysis of USAF remotely piloted aircraft mishaps	Maj Matthew T. Taranto, USAF	FY13
A systems engineering analysis of unmanned maritime systems for U.S. Coast Guard missions	LT James B. Zorn, USCG	FY13
Tailorable Remote Unmanned Combat Craft (TRUCC)	Systems Engineering Analysis Cross-Campus Study (SEA 18B)	FY12
Autonomous Dirigible Airships: a Comparative Analysis and Operational Efficiency Evaluation for Logistical Use in Complex Environments	LT Brian Acton, USN LT David Taylor, USN	FY12
An Interpolation Approach to Optimal Trajectory Planning for Helicopter Unmanned Aerial Vehicles	Maj Jerrod Adams, U.S. Army	FY12
Implementation of Autonomous Navigation And Mapping Using a Laser Line Scanner on a Tactical Unmanned Vehicle	Maj Mejdi Ben Ardhaoui, Tunisian Army	FY12
An Analysis of Undersea Glider Architectures and an Assessment of Undersea Glider Integration into Undersea Applications	Mr William P. Barker	FY12
Integration of an Acoustic Modem onto a Wave Glider Unmanned Surface Vehicle	ENS Joseph Beach, USN	FY12
Investigation of Propagation in Foliage Using Simulation Techniques	LCDR Chung Wei Chan, Republic of	FY12

	Singaporean Navy	
Joint Sensing/Sampling Optimization for Surface Drifting Mine Detection with High-Resolution Drift Model	LT Kristie M. Colpo, USN	FY12
Does China Need A "String Of Pearls"?	Capt Martin Conrad, USAF	FY12
Unmanned Aircraft Systems: A Logical Choice For Homeland Security Support	Maj Bart Darnell, USAF	FY12
Multi-Agent Task Negotiation Among UAVs	Mr. Michael Day	FY12
Optimized Landing of Autonomous Unmanned Aerial Vehicle Swarms	Maj Thomas F. Dono, USMC	FY12
An Analysis of the Manpower Impact of Unmanned Aerial Vehicles (UAV's) on Subsurface Platforms	LT Thomas Futch, USN	FY12
Clock Synchronization through Time-Variant Underwater Acoustic Channels	LCdr Pascal Gagnon, Canada	FY12
UAV to UAV Target Detection And Pose Estimation	Capt Riadh Hajri, Tunisian Air Force	FY12
A Cost-Benefit Analysis Of Fire Scout Vertical Takeoff And Landing Tactical, Unmanned, Aerial Vehicle (VTUAV) Operator Alternatives	CDR Kevin L. Heiss, USN	FY12
Autonomous Parafoils: Toward a Moving Target Capability	CDR Chas Hewgley, USN	FY12
Design and Development of Wireless Power Transmission for Unmanned Air Vehicles	Captain Chung-Huan Huang, Taiwan (Republic of China) Army	FY12
Adaptive Speed Controller for the Seafox Autonomous Surface Vessel	LT Michael A. Hurban, USN	FY12
Coordination and Control for Multi-Quadrotor UAV Missions	LT Levi C. Jones, USN	FY12
An Analysis of the Best-Available, Unmanned Ground Vehicle in the Current Market, with Respect to the Requirements of the Turkish Ministry of National Defense	LT Serkan Kilitci, Turkish Navy LT Muzaffer Buyruk, Turkish Army	FY12
Underwater Acoustic Network As A Deployable Positioning System	ENS Rebecca King, USN	FY12
Business Case Analysis of Medium Altitude Global ISR Communications (MAGIC) UAV System	Ramesh Kolar	FY12
The EP-3E vs. the BAMS UAS An Operating and Support Cost Comparison	LT Colin G. Larkins, USN	FY12
Global Versus Reactive Navigation for Joint UAV-UGV Missions in a Cluttered Environment	ENS Michael Martin, USN	FY12
Bridging Operational and Strategic Communication Architectures Integrating Small Unmanned Aircraft Systems as Airborne Tactical Communication	Maj Jose D. Menjivar, USMC	FY12

Vertical Nodes		
The Aerodynamics of a Maneuvering UCAV 1303 Aircraft Model and its Control through Leading Edge Curvature Change	ENS Christopher Medford, USN	FY12
Future of Marine Unmanned Aircraft Systems (UAS) in Support of a Marine Expeditionary Unit (MEU)	Maj Les Payton, USMC	FY12
Wave-Powered Unmanned Surface Vehicle as a Station-Keeping Gateway Node for Undersea Distributed Networks	LT Timothy Rochholz	FY12
GSM Network Employment on a Man-Portable UAS	LT Darren J. Rogers, USN	FY12
New Navy Fighting Machine in the South China Sea	LT Dylan Ross, USN LT Jimmy Harmon, USN	FY12
Business Case Analysis of Cargo Unmanned Aircraft System (UAS) Capability in Support of Forward Deployed Logistics in Operation Enduring Freedom (OEF)	LT Jason Staley, USN Capt Troy Peterson, USMC	FY12
Application Of An Entropic Approach To Assessing Systems Integration	Mr Hui Fang Evelyn Tan, Republic of Singapore	FY12
Advanced Undersea Warfare Systems	Systems Engineering Analysis Cross-Campus Study (SEA 17B)	FY11
The Dispersal Of Taggant Agents With Unmanned Aircraft Systems (UAS) In Support Of Tagging, Tracking, Locating, And Identification (TTLI) Operations	Capt Dino Cooper, USMC	FY11
Adaptive Reception for Underwater Communications	LTJG Spyridon Dessalermos, Hellenic Navy (Greece)	FY11
The Design and Implementation of a Semi-Autonomous Surf-Zone Robot Using Advanced Sensors and a Common Robot Operating System	LT Steve Halle, USN LT Jason Hickle, USN	FY11
Probabilistic Search on Optimized Graph Topologies	Major Christian Klaus, German Army	FY11
Brave New Warfare Autonomy in Lethal UAVS	LT Matthew Larkin, USN	FY11
Agent-based simulation and analysis of a defensive UAV swarm against an enemy UAV swarm	Lieutenant Mauricio M. Munoz, Chilean Navy	FY11
Derivation of River Bathymetry Using Imagery from Unmanned Aerial Vehicles (UAV)	LT Matthew Pawlenko, USN	FY11
Design Requirements For Weaponizing Man-portable UAS In Support Of Counter-sniper Operations	Maj Derek Snyder, USMC	FY11

Self-propelled semi-submersibles the next great threat to regional security and stability	LT Lance J Watkins, USN	FY11

APPENDIX C: COMMUNITY

This is a representative listing of the CRUSER community of interest inFY16. It is not meant to be inclusive, but is included to demonstrate depth and breadth of interest.

ACADEMIA:

Air Force Institute of Technology (AFIT)
Air Force Junior Reserve Officer Training Corps Jefferson High School
Air Law Institute
Alaska Center for Unmanned Aircraft Systems Integration
American University
Applied Physics Laboratory
Applied Physics Laboratory - University of Washington (APLUW)
Argonne National Laboratory, University of Chicago
Arizona State University (ASU)
Auburn University
AUV IIT Bombay
AUVSI Foundation
Bangalore Robotics
Ben-Gurion University of the Negev
Berkley
Cal Poly San Luis Obispo
California Polytechnic Institute
California State University Long Beach (CSULB)
California State University Monterey Bay (CSUMB)
CalWestern School of Law
Carl Hayden High School
Carnegie Mellon University
Carnegie Mellon University Silicon Valley
Case Western Reserve University
Center for Unmanned Aircraft Systems (C-UAS)
Chapman University
Chosun University
Community College of Baltimore County
Cornell University AUV
Daniel H. Wagner Associates
Doolittle Institute
Drexel University
Embry-Riddle Aeronautical University
Embry-Riddle Aeronautical University/ERASU-Prescott
Faculty of Engineering of the University of Porto (FEUP)

Florida Atlantic University
Florida Institute for Human Machine Cognition
For Inspiration and Recognition of Science and Technology (FIRST)
Francis Parker School
French Air Force Academy
George Washington University (GWU)
Georgia Institute of Technology
Georgia Tech Research Institute (GTRI)
Howard University
Imperial College London
Indian Institute of Science Education and Research-Thiruvananthapuram (IISER-TVM)
Indiana State University
Institute for Homeland Security Solutions (IHSS)
Johns Hopkins University Applied Physics Laboratory (JHU/APL)
Kansas State University
Kasetart University
Kennesaw State University
Kent State University
Ludwig Maximilians Univeristat
Macquarie University
Marine Advanced Technology Education (MATE) Center
Maritime State University
Massachusetts Institute of Technology (MIT)
McGill University
Memorial University of Newfoundland
Mississippi State University
MIT Lincoln Laboratory
Monterey Peninsula College (MPC)
Naval Air Warfare Center (NAWC)
Naval War College (NWC)
Netherlands Defence Academy/Eindhoven University of Technology /TNO/Delft University of Technology
New Mexico State University
North Carolina State University
North Carolina State University (ITRE)
Northwestern University
Notre Dame
Ohio State University
Oklahoma State University
Old Dominion University
Oregon Institute of Technology
Oregon State University (OSU)
Palo Alto High School

Penn State University (PSU)
Penn State Applied Physics Laboratory (PSU/APL)
Rensselaer Polytechnic Institute (RPI)
Saint Louis University
San Diego Christian College
San Diego City College
San Diego State University
SDSU/Faster Logic LLC
Seaside High School
Sinclair College
Southwestern College
St. Georges College
St. Mary's University
Stanford University
SUNY Stony Brook
Teach for America
Technion
Technische Universität München (TUM)
Texas A & M University - Corpus Christi
Texas A&M University
Thomas Jefferson High School for Science and Technology
U.S. Coast Guard Auxiliary
U.S. Naval Academy (USNA)
UK National Oceanography Centre
University of California, Davis
University of California Los Angeles - Anderson
University at Buffalo
University of Alabama
University of Alaska at Fairbanks
University of Arizona
University of California Davis
University of California San Francisco
University of California Merced
University of Central Florida (UCF)
University of Colorado Boulder
University of Dayton Research Institute
University of Florida (UF)
University of Hawaii
University of Hawaii Hilo
University of Idaho
University of Iowa
University of Maryland
University of Maryland UAS Test Site

University of Memphis
University of Michigan
University of Nevada, Las Vegas
University of New Brunswick
University of North Carolina at Charlotte
University of North Dakota
University of Notre Dame
University of Oklahoma
University of Pittsburgh
University of Quebec in Montreal
University of South Carolina
University of South Florida
University of Southern California (USC)
University of Texas
University of Texas at Arlington Research Institute (UTARI)
Unmanned Vehicle University
Utah State Space Dynamics Lab
Utah State University
Virginia Tech
Wichita State University

GOVERNMENT:

1st Force Reconnaissance Company
1st Marine Aircraft Wing (VMU-3)
1st Intelligence Battalion
26th Special Tactics Squadron
25th Air Force
314th Military Intelligence Battalion
3rd Marine Aircraft Wing
412th Test Wing
413th Flight Test Squadron
432nd Operational Support Squadron
526th Intelligence Squadron
548th Intelligence, Surveillance, and Reconnaissance Group
79th Infantry Brigade Combat Team (IBCT)
88th Test and Evaluation (T&E) Squadron
9th Communication Battalion, I MEF
9th Intelligence Squadron
Air Education and Training Command (AETC)
Air Force Institute of Technology (AFIT)
Air Force Research Laboratory (AFRL)
Air National Guard
Air Test & Evaluation Squadron 30
Allied Command Transformation

DOE Argonne National Laboratory
Armstrong Flight Research Center
Assistant Secretary of the Navy for Research, Development and Acquisition (ASN(RDA))
Assistant Secretary of Defense for Research and Engineering (ASD(R&E))
Commander U.S. 3rd Fleet (C3F)
CNAP N809A - UAS Requirements
CNO Rapid Innovation Cell (CRIC)
CNO Strategic Actions Group
CNRC Region West
COMCARSTRKGRU TWO
COMDESRON 31
COMNAVSURFOR
COMPACFLT
COMPACFLT (N9)
COMPATRECONWING ELEVEN
COMPATRECONWING TWO
COMPATRECONWING TWO (N7)
COMPHIBRON EIGHT
Commander, Submarine Forces (SUBFOR)
COMSUBPAC (Code N7C)
COMSUBPAC / CTF 34
COMTACGRU ONE
Commander, U.S. 3rd Fleet (COMTHIRDFLEET)
COMUSNAVSOUTH
CSDS-12
CSDS-5
CSG2
Customs and Border Protection (CBP)
CBP National Air Security Ops Center
CVN 68
DASN
Defense Advanced Research Projects Agency (DARPA)
DARPA Tactical Technology Office
Defense Innovation Unit Experimental (DIUx)
Defense Intelligence Agency (DIA)
Defense Language Institute (DLI)
Defense Manpower Data Center (DMDC)
Defense Threat Reduction Agency (DTRA)
Department of Defense (DoD)
Department of Energy (DOE)
Department of Homeland Security (DHS)
Department of Justice (DOJ)
Department of State (DOS)

Department of the Interior (DOI)
DHS Immigration and Customs Enforcement (ICE)
DoD Office of the Inspector General (OIG)
DoD Unexploded Ordnance Center of Excellence
Department of the Navy Assistant for Administration (DON/AA)
DOT Office of the Inspector General
DUSN (Policy)
Expeditionary Strike Group Three
FAA Headquarters
FAA Western-Pacific Region
FCOE
Federal Aviation Administration (FAA)
Federal Emergency Management Agency (FEMA)
FFI
Fleet Readiness Center SouthWest
Fleet Survey team
Flight Global
Fleet Numerical Meteorology and Oceanography Center (FNMOC)
Futures Assessment Division, MCWL, MCCDC
Helicopter Sea Combat Wing Pacific
HHS/ASPR
HQ NORAD
HQMC
HQMC Installations & Logistics
HSC-3
HSCWINGPAC
HSM Weapons School Pacific
HSM-35
HSM-71
HSM-78
I MEF
I2WD TFE
Irregular Warfare Technology Office
Joint Counter Low, Slow, Small UAS (JCLU)
Joint Counter Low, Slow, Small Unmanned Aircraft Systems Joint Test
Joint Integrated Air & Missile Defense Organization (J8)
Joint Staff J-7
Joint Staff Remote/Unmanned Futures Office
Joint Vulnerability Assess. Branch
JS J-7, Future Joint Force Development
JUAS COE
JWAC
Lawrence Livermore National Laboratory (LLNL)

Littoral Combat Ship Anti-Submarine Warfare Mission Package Detachment 2 (LCS ASW MP DET 2)
Maneuver Center of Excellence, Maneuver Battle Lab
MARCORSYSCOM
MARFORPAC Experimentation Center
Marine Corps Warfighting Lab (MCWL)
MCWL Center for Emerging Threats and Opportunities (CETO)
Marine Unmanned Aerial Vehicle Squadron 4
MAWTS-1
MCIOC
MI Air National Guard
N2N6E7
N3N5IW
N8
NAE CTO
NAS Patuxent
National Aeronautics and Space Administration (NASA)
NASA Aeronautics Research Mission Directorate (ARMD)
NASA Ames Research Center
NASA Jet Propulsion Laboratory (JPL)
NASA Johnson Space Center (JSC)
NASA Langley Research Center
NASA-JSC
National Defense University (NDU)
National Geospatial-Intelligence Agency
National Guard Bureau
National Oceanic and Atmospheric Administration (NOAA)
National Science Foundation (NSF)
National Transportation Safety Board
Naval Air Systems Command (NAVAIR)
NAVAIR Point Mugu Sea Range
NAVAIR - UASTD
NAVAIR Code 410
NAVAIR/PMA-266
Naval Air Warfare Center Aircraft Division (NAWCAD)
Naval Air Warfare Center Patuxent River
Naval Air Warfare Center Training Systems Division
Naval Air Warfare Center Weapons Division (NAWCWD)
NAVFAC CIOFP1
NAVFAC HQ
Naval Mine & ASW Command
Naval Oceanographic Office (NAVO or NAVOCEANO)
Naval Oceanography and Mine Warfare Center

Navy Office of General Counsel
Naval Postgraduate School (NPS)
Naval Research Laboratory (NRL)
Naval Sea Systems Command (NAVSEA)
NAVSEA O5L
NAVSEA Port Hueneme
NAVSEA SEA05L
NAVSEA LOGCEN
Naval Special Warfare Group 3 (NAVSPECWARGRU THREE)
Navy PEO LMW PMS 408
Navy Recruiting District, San Diego
Navy Region Southwest
Navy Special Warfare Command
Navy TENCAP
Navy, Office of the General Counsel
Naval Air Warfare Center (NAWC)
NAWC Weapons Division (NAWCWD) China Lake
NAWC Training Systems Division (NAWCTSD)
NAWC Aircraft Division (NAWCAD)
Naval Base Ventura County (NBVC) Pt. Mugu
Naval Criminal Investigative Service (NCIS)
Navy Cyber Warfare Development Group (NCWDG)
Navy Expeditionary Combat Command (NECC)
NMAWC
NMAWC Detachment Norfolk
NORAD - USNORTHCOM
NORAD-NORTHCOM
NORAD-USNORTHCOM (UAS-AI)
NR NSW INTEL 17
NSW Group 11
NSW SPECRECON TWO
Naval Surface Warfare Center (NSWC)
Naval Surface Warfare Center Carderock Division (NSWCCD)
Naval Surface Warfare Center Crane Division
Naval Surface Warfare Center Dahlgren Division (NSWCDD)
NSWCDD/W16
NSWC Indian Head Division (NSWC IHDIV)
NSWC Indian Head Explosive Ordnance Disposal Technology Division (NSWC IHEODTD)
NSWC Norfolk
NSWC Panama City Division (NSWCPCD)
NSWC Port Hueneme Division (NSWCPHD)
Naval Undersea Warfare Center (NUWC)
NUWC Keyport (KPT)

NUWC Newport (NUWCDIVNPT or NPT)
NUWCDIVKPT DETPAC Kauai OS//PMRF
Navy Warfare Development Command (NWDC)
NWDC/DAWCWD
Office of Naval Intelligence (ONI)
Office of Senator Kirsten E. Gillibrand
Office of the Secretary of Defense (OSD)
Office of the Under Secretary
Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD(AT&L))
Office of Naval Research (ONR)
ONR Reserve Component (ONR-RC)
ONR/NRL S&T Detachment 113
ONR Global (ONRG)
ONR 322
ONR 34
ONR P38
Office of the Chief of Naval Operations (OPNAV)
OPNAV N2/N6
OPNAV N2/N6F22
OPNAV N415
OPNAV N51
OPNAV N97
OPNAV N98
Program Executive Office Command, Control, Communications, Computers & Intelligence (PEO C4I)
PEO C4I Undersea Integration (PMW 770)
PEO C4I Carrier and Air Integration (PMW 750)
Program Executive Office Ground Combat Systems (PEO GCS) Robotics Systems Joint Project Office (RSJPO)
PEO Littoral Combat Ship Fleet Introduction (PMS 505)
PEO LCS Mine Warfare (PMS 495)
F/A-18 and EA-18G Program Office (PMA 265)
Program Office Unmanned Carrier Aviation (PMA 268)
Robotic Systems Joint Project Office (RSJPO)
RS Special Research Access
Sandia National Laboratories
Secretary of the Navy (SECNAV)
Space and Naval Warfare Systems Command (SPAWARSYSCOM)
SPAWAR System Center Pacific (SSC Pacific)
SPAWAR System Center Atlantic (SSC Atlantic)
Stennis Space Center Fleet Survey Team
Submarine Development Squadron 5 (COMSUBDEVRON FIVE) or CSDS-5
SUBDEVRON FIVE Detachment UUV

Submarine Development Squadron 12 (COMSUBDEVRON TWELVE) or CSDS-12
Submarine Officers Advanced Course
Tactical Training Group Pacific (TACTRAGRUPAC) San Diego CA
The Joint Staff
DoD Unexploded Ordnance Center of Excellence (UXOCOE)
U.S. Air Force (USAF)
U.S. Air Force Academy (USAFA)
Air Force Joint Information Operation Range (JS/JIOR)
U.S. Army
Army Aero Services Agency
Army Capabilities Integration Center
Army Communications-Electronics Research, Development and Engineering Center (CERDEC) Night Vision Lab
U.S. Army Joint Base Lewis-McChord (Fort Lewis)
U.S. Army Redstone Arsenal
AMC/RDECOM/AMRDEC
Army Research, Development and Engineering Command (RDECOM)
Army Research Laboratory (ARL)
U.S. Army Special Operations Command (USASOC)
Army S&T
U.S. Army Tactical Command (TACOM)
Army Test and Evaluation Command (ATEC)
U.S. Army Training and Doctrine Command (TRADOC) Analysis Center
Army Unmanned Aircraft Systems
U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC)
U.S. Central Command (CENTCOM)
U.S. Coast Guard (USCG)
U.S. Coast Guard Headquarters
USCG Research & Development Center
U.S. European Command (EUCOM)
U.S. Fleet Forces Command (USFF)
USFF N72
U.S. Marine Corps (USMC)
USMC Pentagon
U.S. Marshall Service
U.S. Military Academy (USMA)
U.S. Naval Test Pilot School
U.S. Naval Special Warfare Command (NAVSPECWARCOM)
U.S. Navy Air Test and Evaluation Squadron THREE ZERO (VX-30)
U.S. Navy Fleet Logistics Support Squadron Five (VR-55)
U.S. Navy Reserve (USNR)
U.S. Pacific Command (PACOM)
U.S. Northern Command (NORTHCOM)

U.S. Secret Service
U.S. Southern Command (SOUTHCOM)
U.S. Special Operations Command (SOCOM)
U.S. Special Operations Command Africa (SOCAFRICA)
U.S. Special Warfare Command (SPECWARCOM)
U.S. Strategic Command (STRATCOM)
U.S. Transportation Command (TRANSCOM)
USS Chung-Hoon
USS McCampbell
Unmanned Patrol Squadron ONE NINE
Unmanned Systems Team, MBL
UxS Cross Functional Team
VIRGINIA Class Program Office
California Department of Insurance Fraud
California Department of Motor Vehicles - Investigations
California Emergency Management Agency (Cal EMA)
California Highway Patrol (CHP)
State of Alaska Department of Transportation
Georgia Emergency Management and Homeland Security Agency (GEMHSA)
State of Oklahoma
Oklahoma Dept of Commerce
Business Oregon
State of Utah - Economic Development Office
State of Utah, Governor's Office Economic Development
State of Wisconsin
Wisconsin Department of Justice (DOJ) Division of Criminal Investigation (DCI)
Arlington County Police
Bakersfield Police Department
Banning Police Dept
Calexico Police Department
Chicago Fire Department
City of Frisco
City of Las Vegas
Cleveland VA Medical Center
CSU Fresno Police
Eldorado Sheriff's Office
Elk Grove Police Department
Fremont Police Department
Irvine Police Department
Marin County Sheriff
Monterey County Sheriff
Mountain View Police Department
Oakland Police Department

Ontario International Airport
Oklahoma City Chamber of Commerce
Riverside County District Attorney Office
Sacramento County Sheriff
Sacramento Office of Emergency Services
Sacramento Police Department
San Diego Sheriff's Department
San Leandro Police Department
San Mateo County Sheriff
San Mateo Police Department
Tulsa Chamber of Commerce
Tustin Police Department
Ventura County Economic Development Association
Ventura County Sheriff
Ventura Police Department
Visalia Police Department
North Atlantic Treaty Organization (NATO)
Australian Defence Force Academy AUSTRALIA
Defence Science & Technology Group AUSTRALIA
Royal Australian Navy AUSTRALIA
Brazilian Navy BRAZIL
Canadian Forces Aerospace Warfare Centre CANADA
Canadian Forces Maritime Warfare Centre CANADA
Transport Canada Safety & Security CANADA
Business France FRANCE
Egyptian Naval Forces EGYPT
Hellenic Navy GREECE
Italian Navy ITALY
Mexican Navy MEXICO
Agency for Defence Development (ADD) SOUTH KOREA
Royal Swedish Navy SWEDEN
Swedish Defence Material Administration SWEDEN
Swedish Naval Warfare Center SWEDEN
Turkish Air Force TURKEY
Turkish Navy TURKEY
UK Ministry of Defense UNITED KINGDOM
British Consulate - General LA* UNITED KINGDOM

INDUSTRY:

0cog Inc.
2d3 Sensing
3D PARS - 3D Printing and Advanced Robotic Solutions
5D Robotics
AAI Corporation

Abbott Laboratories
Abbott Technologies
ACADEMI
Access Spectrum
ACE Applied Composites Engineering
ACSEAC
Aviation Comm & Surveillance Systems (ACSS), LLC
ACT
Action Drone
Accelerated Development & Support (ADS) Corporation
Atlantic Diving Supply (ADS) Inc.
ADSYS Controls Inc
Advanced Acoustic Concepts
Advatech Pacific
AEgis Technologies
Aerial MOB
Aero UAVs
AeroEd Group
Aerofex Corp
Aerojet Rocketdyne
Aeropsace Corp
Aerospace Analytics, LLC
AeroTargets International
Aerovel Corp
AeroVironment
Affordable Engineering Services
Ag Eagle
AgriSource Data, LLC
Air Concepts Group
Air View Consulting
AIRBUS Defense & Space
Airspeed Equity
Airware
ALAKAI Defense Systems
Alaris Pro
Alaska Aerospace Corporation
Alternative Experts, LLC (ALEX)
Alidade Incorporated
Alpha Research & Technology, Inc.
Alta Devices
Altair
Altron
Amazon

American Autoclave Co
AMP Research, Inc.
Andro Computational Solutions
ANT Global Services
Antonelli Law
Abbott On Call (AOC), Inc.
Applied Mathematics, Inc.
Applied Physical Sciences Corp
Applied Research Associates Inc.
Applied Research in Acoustics
Applied Visions, Inc.
Applied Physical Sciences Corp.
Arcturus UAV
Argon Corp
Argon ST
Arkwin Industries, INC.
Arnouse Digitall Device Corp
Artemis
Advanced Scientific Concepts, Inc. (ASC)
Aeronautical Systems, Inc. (ASI)
ASV Global
Asylon
Alexander Technical Coordinators, LLC
Advanced Technology International (ATI)
Atlas North America
AuraTech Engineering (ATE)
Aurora Flight Sciences
Ausley Associates, Inc.
Autonomous Avionics
AVIAN LLC
Avineon, Inc.
Axiom Electronics
B. E. Meyers
Bacolini Enterprises
BAE Systems
Ball Aerospace & Technologies Corp
Barry Aviation
Battelle Memorial Institute
Battlespace Inc
BBN Technologies
BecTech
Bell Helicopter Textron, Inc.
BGI Innovative Solutions

Bicallis, LLC
Black & Veatch Special Projects Corp.
Blackbird Technologies
Blackhawk Emergency Management Group
Bluefin Robotics Corporation
BMNT Partners
Boeing
Boomerang Carnets
Booz Allen Hamilton (BAH)
Borchert Consulting and Research AG
BOSH Global Services
Bosh Technologies
Boston Engineering Corporation
Bot Factory
Bramer Group LLC
Broadcast Microwave Services Inc. (BMS)
BRPH
C-Astral
C2i Advanced Technologies
Cabrillo Technologies
CACI
Calvert Systems
Camber Corp
CANA LLC
CAPCO LLC.
CapSyn (Capital Synergy Partners, INC.)
Carnegie Robotics
CAST Navigation
CDI Marine
Center for a New American Security
Center for Applied Space Technology
CenterState Corporation for Economic Opportunity
CENTRA Technology, Inc.
CENTUM
Channel Technologies Group (CTG)
Charles River Analytics
CHHOKAR Law Group
CHI Systems
Chinwag
CISCO
Clarity Aero
Clear-Com
CLK Executive Decisions

CNA Analysis & Solutions
Cobham plc
Codan Radio Communication
Coherent Technical Services, Inc.
Colby Systems Corporation
Comphydro Inc
Compsim LLC
Comtech Solutions LLC
Concepts to Capabilities Consulting LLC
Conoco Phillips Company
Consolidated Aircraft Coatings
Copeasctic Engineering
Cornerstone Research Group
Cornet Technology
Corning
Corsair Engineering
Communications & Power Industries LLC (CPI)
Crystal Group Inc.
Charles Stark Draper Laboratory, Inc.
CSCI - Computer Systems Center Inc.
CS-Solutions Inc
CT Johnson & Associates
CTJA, LLC
CUBIC
Cutting Edge
Cyber Security & IS IAC (CSIAC)
CyberWorx
CyPhy Works
David Ricker Group, LLC
Dayton Development Coalition
DDL Omni
Defense Materiel Organisation
Del Rey Sys. & Technology Inc.
Delta Airlines
Delta Digital Video
Desert Star Systems
Digital Adopxion
Digital Harvest
Diversified Business Resources, Inc.
DOER Marine
Domo Tactical Communications
Dove Innovations
DPI UAV Systems

DPSS Lasers
DRA - Defense Research Associates
Dragonfly Pictures
DREAMHAMMER
D-RisQ
Drone America
Drone Aviation Corp
Drone Logger Enterprise
Drone Pilots Federation
Drone Services Hawaii
DroneBase
Dronecode
Dronomy
DST Control
Duzuki
E.J Krause & Associates
EC Wise
ECC
Ehang
Elbit Systems
ELG Inc
Electricore
Electro Rent Corporation
Elementary Institute of Science
Ellevision, LLC
Elmo Motion Control
Emerging Technology Ventures Inc.
Engility, Inc
Engineered Packaging Solutions
EnrGies
EQC, Inc
ERA
Ervin Hill Strategy
ESRI
Esterline Control & Communication Systems
Eutelsat America
Exelis Inc
FABLAB San Diego
Fairchild Imaging
Farm Space Systems LLC
Faun Trackway USA
FEI-Zyfer Inc.
Felix Associates

Five Rivers Services, LLC
Flagship Government Relations
FLIR Systems, Inc.
FLYCAM UAV
FORSCOM Aviation Directorate
FreeFlight Robotics
Freescale
FreeWave Technologies Inc.
Frost & Sullivan
Fugro Geoservices Inc.
G2 Solutions
Galois Inc.
GC Ventures
GE Aviation
General Atomics
General Atomics Aeronautical
General Atomics Aeronautical Systems
General Atomics Aerospace
General Atomics ASI
General Dynamics
General Dynamics Advanced Information Systems
General Dynamics Information Technology (GDIT)
General Dynamics Land Systems
General Dynamics Mission Systems
Geospatial San Diego
Germane Systems
GET Engineering
Getac
Gibbs & Cox, Inc.
GL INTERNATIONAL
Global Technical Systems
Go Profressional Cases (GPC)
Gold Star Strategies LLC
Goleta Star LLC
GPH Consulting
Griffon Aerospace
Grupo Senseta Inc.
Gryphon Technologies LC
Gryphon Sensors LLC
GTS Consulting
H.O. JOHNSON RESULTANTS LLC
Harris Communications
Harwin

Hawaii Hazards Awareness & Resillience Program
Herley Lancaster
High Eye BV
Hoggan Lovells LLP
Honeywell
Hughes
Hydr0 Source LLC
Hydroid
Hyperspectral Imaging Foundation
IBM
IC2S (Innovative C2 Solutions, LLC.)
iDEA Hub
IEEE ICSC2015
IHI
Ike GPS
Image Insight
Implevation, LLC
IMSAR
Independent Wireless Executive
Information Processing Systems, Inc
Inmarsat
Innoflight
Innovative Computing & Technology Solutions, LLC
INOVA Drone
Inside Umanned Systems
Insight Global
Insights
Insitu, Inc.
Intelligent Automation
InterContinental IP
Intergraph Gov Solutions
Iris Technology
iRobot
ITA International
IXI Technology
JACOBS
Janes Capital Partners
Japan Aerospace Exploration Agency
JHNA
JOBY Aviation
John Deere
Joint Venture Monterey Bay
Jove Sciences, Inc.

Juniper Unmanned
Kairos Autonomi
Kairos Autonomomi
Kaman
Ken Cast
Kitware
Knife Edge
KNOWMADICS
Kongsberg
Kraken
Kratos Defense & Security Solutions, Inc.
L-3 Communications, Inc.
Laser Shot
Latitude Engineering
Liverpool Data Research Associates (LDRA)
Leidos
Lenny Schway Photography
Leucadia Group
LIG Nex1 SOUTH KOREA
Lightspeed Innovations
Liquid Robotics, Inc.
Llamrai Enterprices
Lockheed Martin Aeronautics Company
Lynntech
Magnet Systems
Makani Power Inc
Make in LA
MAMM 3D Inc.
Management Sciences, Inc
MAPC (Maritime Applied Physics Corp)
Maplebird
Marine Acoustics
Maritime Applied Physics Corporation
Maritime Tactical Systems, Inc. (MARTAC)
Martin UAV
MASI LLC
Materials Systems Inc.
Materion
MBDA Incorporated
McBee Strategic
McCauley Prop Systems
McClean Group
McKenna, Long & Aldridge LLP

MCR Critical Thinking Solutions Delivered
MDA Corporation
Medweb
Merlin Global Services
Mesa Technologies
Metal Technology
Metcon Aerospace & Defense
Micro Engineering Tech, Inc. (METI)
Metron Inc.
Michael Baker International
Micro USA Inc.
Microflown
MicroPilot
Microwave Monolithics Inc
Middle Canyon LLC
MilSource
Miltrans
MINCO
MISTIC INC
Mistral Inc
MIT Enterprise Forum San Diego
MITRE Corporation
Modern Technology Solutions, Inc.
Modus Robotics
Momentum Aviation Group
Monterey County Herald
Moog Inc
Morrison & Foerster LLP
MosaicMill
MRU Systems
MSI
MTSI - Modern Technology Solutions
Multi GP
Murtech Inc.
Nano Motion
Nanomotion
NASC
National Science & Technology Corp.
Nautilus
Naval Nuclear Laboratory
NAVPRO Consulting LLC
Near Earth Autonomy
Netzer Precision Motion Sensors Ltd.

Newport News Shipbuilding
Next Vision Stabilized Systems Ltd
Nexutech, Ltd
Neya Systems LLC
NiederTron Robotics
NLD MOD (Defence Materiel Org
NNS
Northeastern University
Northrop Grumman
Northrop Grumman (NGC)
Northrop Grumman Corporation
Northrop Grumman Inc.
NorthWind
Novel Engineering
NV Drones
NWB Environmental Services
NWUAV Propulsion Systems
Ocean Aero
Ocean Lab
Ocean Wings UAS, Inc.
Oceaneering
ODNI
Odyssey Marine Exploration
Ontario Drive & Gear
OPNAV Safety Liason
Optical Cable Corp.
Oracle
Orca Maritime, Inc.
Orion Systems
Orions Systems
ORYX
Oxford Technical Solutions
P11 Consulting
Pacific Science & Engineering Group
Pacific Synergistics International (PSI)
Pappas Associates
Paradigm
Paragrine Systems
Parsons
Paso Robles Ford
Patuxent Partnership
Paul R Curry & Associates
Pentagon Performance Inc.

People Tec
perceptronics solutions
Perforce
Perkins COIE
Persistent Systems
PG&E
Phantom Works
Physical Optics Corp
Pixiel FRANCE
PIXIA
Polarity
Pole Zero
Power Correction Systems Inc.
Power Ten Incorporated
Power4Flight LLC
Praxis Aerospace Concepts International
Precision
PREMANCO Ventures
Prescient Edge
Prescision
Princeton Lightwave
Prioria Embedded Intelligence
Profit Quadro
Progeny Systems
Promia
Propellerheads
Provectus Robotics Solutions
Prox Dynamics
Proxdynamics
Proxy Technologies
q-bot
QinetiQ
QUALCOMM
Quanterion Solutions Incorporated
Quartus Engineering
Quatro Composites
R Lynch Enterprises
R-3 Consulting
R3SSG
Rajant
Ramona Research
Rand Corporation
Randiance Technologies

Range Networks
Rapid Imaging Software
Raytheon
Raytheon Company - Integrated Defense Systems
Red Hat, Inc.
Red Six Solutions
Redwall Technologies
Reference Technologies Inc.
Renaissance Strategic Advisors
RFMD
Riegl USA
Riptide Autonomous Solutions
RIX Industries
RJ Vincent Enterprises LLC
RMV Technology Group
ROBOTEAM
Robotic Research
Rockwell Collins
Rocky Mountain Institute
Rogue Tactical LLC
Rolls Royce
Roving Blue
RT Logic
RTI
Rumpf Associates International
Rupprecht Law
SAAB
Saab Defense and Security USA
SAGE Solutions Group, Inc
SAIC
Saildrone
SAP National Security Services, Inc. (SAP NS2)
SAS Institute
Scale Matrix
SCD.USA Infrared LLC
Scientific Applications & Research Associates
Scientific Research Corporation (SRC)
Scorpion Aerosystems Inc
Scoutsman Unmanned LLC
Sculpture Networks Inc.
SDG&E
Sea Phantom International, Inc
SeaBotix

Seamatica Aerospace Limited
Seapower Magazine
SebastianConran/associates
SEKAI
Selex Galileo Inc.
Semantic Computing Foundation
Sematica Aerospace Limited
Senior Program Associate at AAAS
Senior Systems Engineering Consultant Unmanned Systems and C4ISR
Senseta Inc
Sensintel
sensonor
Sensurion Aerospace
Sentinel Robotic Solutions (SRS)
SES Govt Solutions
SETA / ONR
Seven Seals
Shadow (Robot Company)
Shephard Media
Shoof Technologies
Show Pro Industries
Sierra Nevada Corp
SIFT (Smart Info Flow Technologies)
Sightline Media Group
Signal Monitoring Solutions, Inc.
Signature Science
Sikorsky
Silent Falcon UAS Technologies
Silvus Technologies
Simlat, Ltd.
SIRAB Technologies Inc
SKYEYE GLOBAL
Skylift Global
Smith Currie & Hancock
SNC - Sierra Nevada Corporation
Soar Oregon
Soar Technology, Inc.
Society of Experimental Test Pilots
Soliton Ocean Services, Inc.
Sonalyst, Inc
Sonitus Technologies
Space Micro
Sparton Corporation

Spatial and Spectral Research
Spatial Integrated Systems
Spectrabotics
Spectrum Aeronautical, LLC
Spinner
Spiral Technology, Inc.
Squid Works, Inc.
SRI International
SSL
ST Aerospace
Stark Aerospace Inc.
Steinbrecher & Span LLP
Straight Up Imaging
Strategic Analysis Enterprises
Strategic Defense Solutions, LLC
Stratom
Stryke Industries
Sunhillo Performance Technologies
Sutton James
SwRI (Southwest Research Institute)
Sypris Electronics
Systems Planning and Analysis, Inc. (SPA)
SYZYGYX Incorporated
Tactical Air Support, Inc.
Tapestry Solutions, Inc.
TaSM (Technology and Supply Management) LLC
TCG
Tech Associates, LLC
Tech Incubation
Tech Source
Technology Training Corporation
TechSource
TECOM
Teledyne Marine
Teledyne SeaBotix
Teledyne Brown Engineering
Teledyne RD Instruments
Teledyne Technologies, Inc.
Teledyne Webb Research
Telephonics Corporation
Teletronics
TENTECH LLC
Terrago

Tesla Foundation Group
Tethered Air
Textron Systems
TFD Europe
Thales Australia and NZ
Thales Defense & Security Inc.
The Aerospace Corporation
The Clearing
The Jackson Group
The Maritime Alliance
The MITRE Corporation
The Pilot Group
The Radar Revolution
The Ranger Group
The Spectrum Group
Third Block Group
Tiger Tech Solutions
Tiresias Technologies
Topcon
Torch Technologies
TorcRobotics
Toyon
TP Logic
Trabus
Transportation Power Inc.
Travelers United
Trimble Navigation Ltd
TRIMECH Solutions
Tucson Embedded Systems
Twin Oaks Computing
UAS Colorado
UAS Today
UASolutions Group
UASUSA
UAV Factory
UAV LLC.
UAV Pro
UAV Solutions
UAV Vision
UAVNZ
UCAL-JAP Systems LTD.
Ultimate Satellite Solutions (UltiSat)
Ultra Electronics Group

Ultra Electronics - USSI
UltraCell
Ultra-EMS
Ultravance Corp
UMS3
United Technologies Research Center
Universal Display Corporation
Unmanned Aero Services
Unmanned Power LLC
Unmanned Systems Institute
Unmanned Systems Research & Consulting LLC
Unmanned Vehicle Systems Consulting, LLC
Unmanned World Wide
US Nuclear Corp.
USI
UTC Aerospace Systems
UxSolutions Inc
Van Scoyoc Associates
VCT (Vehicle Control Technologies Inc)
Vector CSP
Velocity Cubed Technologies
Velodyne Acoustics
Veridane
ViaSat
Video Ray LLC
VideoBank
Virtual Agility
Vision Technologies
Vital Alert
VPG Inc
VSTAR Systems Inc.
Vulcan
Wade Trim
Wateridge Insurance Services
WBT Innovation Marketplace
WDL Systems
Whitney, Bradley & Brown Inc. (WBB)
Williams Mullen
Wind River
WINTEC
Wireless SEC Assoc
Woolpert
Wounded Eagle UAS

Wyle
Yamaha Motor Corp. USA
Z Microsystems
ZDSUS
Zepher, Inc.
Zeuss
Zimmerman Consulting Group
Zivko Aeronautics
Zodiac Aerospace
Z-Senz
Zugner LLC

OTHERS:

Aircraft Owners & Pilots Association (AOPA)
Association for Unmanned Vehicle Systems International (AUVSI)
Autonomous Undersea Vehicle Applications Center (AUVAC)
AUVSI Florida Peninsula Chapter
AUVSI Foundation
AUVSI Wright Brothers Chapter
Center for Naval Analyses (CNA)
Institute for Defense Analyses (IDA)
Institute for Religion and Peace
Mine Warfare Association (MINWARA)
Monterey Bay Aquarium Research Institute (MBARI)
Monterey County Weekly
National Defense Industrial Association (NDIA)
National Electrical Manufacturers Association (NEMA)
Nevada Institute for Autonomous Systems
NUAIR Alliance
Salinas Californian
SRC, Inc.
"War Is Boring" blog

APPENDIX D: CRUSER FY16 CALL FOR PROPOSALS

The FY16 call for proposals was released in September 2015, and again was requested in two distinct tracts: 1) Research and 2) Education. Proposals selected for funding are summarized in the second chapter of the full FY16 CRUSER Annual Report.

CRUSER Call for Proposals FY16

Research Track

PROPOSALS DUE DATE:	**3 August 2015**
Selection Date:	**August 2015**
Funding Start Date:	**As early as 1 Oct 15**
Funding Expiration Date:	**30 Sept 2016**
Funding Levels:	**up to $150,000**
Proposal Type:	**Single-Year Proposals**

Research Goal: The Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) at the Naval Postgraduate School provides a collaborative environment for the advancement of educational and research endeavors involving unmanned systems across the Navy and Marine Corps. CRUSER seeks to align efforts, both internal and external to NPS, by facilitating active means of collaboration, providing a portal for information exchange among researchers and educators with collaborative interests, and supporting innovation through directed programs of operational experimentation.

Anticipated Funding Amount: Funding has not yet been received for FY16; however the purpose of this call for proposals is to prepare researchers on campus to begin work as soon as possible in the new fiscal year.

- *CRUSER has travel funding for students beyond project funds, but they will need to complete the standard CRUSER Student Travel request procedure to be approved for this travel support. Students who do not have prior approval to travel on CRUSER funding will be charged to the project.*

Research Focus Areas: CRUSER Innovation Thread 4: Warfare in a Contested Littoral

a) Unconventional UxS Applications
b) Marsupial Robotics
c) Leveraging Natural Systems
d) Deployable Sensor Networks in A2AD Environments
e) Tactical and Operational Employment of Additive Manufacturing
f) Unmitigated Risks of Dependence on UxS in Contested Environments
g) Seafloor Charging Mats
h) EMP Force Field
i) Station-Keeping Tether

NOTE: Proposals for topics related to ANY robotic/unmanned sytems area will be considered. However, researchers are encouraged to relate proposals to an Innovation Thread Reserch Focus Area.

Classification Level: Unclassified (Preferred)

Required Documents: http://CRUSER.nps.edu

1. 1-page executive summary – template provided on http://CRUSER.nps.edu
2. 5-7 page proposal – template with key areas provided on http://CRUSER.nps.edu
3. Current Year Research Office Budget form - http://intranet.nps.edu/ResAdmin/FY15/prop_budg_page.html
4. Quad Chart – template on http://CRUSER.nps.edu

Submission Procedures:

- FY16 CRUSER Proposals and supporting documents should be submitted to cruser@nps.edu (Lisa Trawick, CRUSER Operations Manager). *Do not submit through the Research Office. (Only selected proposals will need to be routed through department/dean/RSPO processes.)*

Review and Selection Board: Proposals will be evaluated by a panel of reviewers co-chaired by the Dean of Research and the CRUSER Director. Any member of the CRUSER coordination group submitting a funding proposal will not serve on the panel.

Proposal Evaluation Criteria:

1) Student involvment
2) Interdisciplinary, interagency, and partnerships with naval labs
3) Partnerships with other sponsors' funding
4) Research related to various unmanned systems' catagories:
    a. Technical
    b. Organization and Employment

c. Social, Cultural, Political, Ethical and Legal
d. Experimentation

5) New research area (seed money to attract other contributors)
6) Research topics related to ANY robotic and unmanned sytems area may be proposed, though proposals related to any CRUSER innovation thread are preferred. (See website and above focus areas)
7) Alignment with SECNAV's DON Unmanned Systems Goals (see *CRUSER Charter* memo)
8) Researchers are members of the CRUSER Community of Interest
9) Proposals should aim to make an immediate impact on the community ($75k - $150k)

Faculty members who receive CRUSER funds are expected to be members of CRUSER AND fully active in supporting CRUSER's goals to include (but not limited to):

- Monthly meeting attendance
- A Presentation at a montly meeting and at the annual CRUSER TechCon
- A CRUSER News article
- Participation in CRUSER sponsored events
- Contributions to the CRUSER Annual Report
- Providing updated labor plans and budget projections as requested

<u>CRUSER Call for Proposals FY16</u>

Education Track

PROPOSALS DUE DATE:	**3 August 2015**
Selection Date:	**August 2015**
Funding Start Date:	**As early as 1 Oct 15**
Funding Expiration Date:	**30 Sept 2016**
Funding Levels:	**up to $150,000**
Proposal Type:	**Single-Year**
Proposals	

<u>Education Goal</u>: The Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) strives to increase knowledge and understanding of robotics and unmanned systems through the innovative use of technology combined with established concepts of education. CRUSER Education Concepts are designed to encourage contributions to this educational goal through the development of educational devices that can help achieve deep intellectual penetration across a broad audience base while maintaining a common theme focused on robotics and unmanned systems. The development and use of robotics and unmanned systems involve a vast and complex web of academic disciplines.

<u>Anticipated Funding Amount</u>: Funding has not yet been received for FY16; however the purpose of this call for proposals is to prepare researchers on campus to begin work as soon as possible in the new fiscal year.

- *CRUSER has travel funding for students beyond project funds, but they will need to complete the standard CRUSER Student Travel request procedure to be approved for this travel support. Students who do not have prior approval to travel on CRUSER funding will be charged to the project.*

<u>Education Focus Areas:</u>

a) **Content**: Develop course or lecture content modules that focus on specific aspects of CRUSER. These modules may be delivered presentations, videos, demonstrations, simulations, or any format that optimizes opportunities to reach, inform and educate intended audiences.

b) **Education Sequencing Plans:**
   a. **Virtual lecture series:** Develop sequencing plans for distribution of synchronous and asynchronous web-based lectures that support the major areas of the CRUSER mission
   b. **Physical lecture series:** Develop sequencing plans for distribution of face-to-face lectures that support various areas of the CRUSER mission
   c. **Distance Learning Project Support:** Develop course material or support information for DL degrees
   d. *If a new course is being developed, a memo stating the Dean's approval must be included.*

c) **Distributed information chunking**: Develop solutions for presenting complex concepts to globally distributed personnel with limited chunks of time to spend online.

d) **Audience Identification**: Analyze the intended audience for CRUSER initiatives and determine the appropriate medium and level of detail for each demographic division

Classification Level: Unclassified

Required Documents: http://CRUSER.nps.edu

5. 1-page executive summary – template provided on http://CRUSER.nps.edu
6. 5-7 page proposal – template with key areas provided on http://CRUSER.nps.edu
7. Current Year Research Office Budget form - http://intranet.nps.edu/ResAdmin/FY15/prop_budg_page.html
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Submission Procedures:

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Review and Selection Board: Proposals will be evaluated by a panel of reviewers co-chaired by the Dean of Research and the CRUSER Director. Any member of the CRUSER coordination group submitting a funding proposal will not serve on the panel.

Proposal Evaluation Criteria:

10) Student involvment
11) Interdisciplinary, interagency, and/or partnerships with naval labs

12) Partnerships with other sponsors' funding
13) Proposer is a teaching faculty member
14) Related to a CRUSER Innovation Thread
15) Alignment with SECNAV's DON Unmanned Systems Goals (see *CRUSER Charter* memo)
16) Researchers are members of the CRUSER Community of Interest
17) Proposals should aim to make an immediate impact on the community($75k - $150k)

Faculty members who receive CRUSER funds are expected to be members of CRUSER AND fully active in supporting CRUSER's goals to include (but not limited to):

- Monthly meeting attendance
- Presentations at a monthly meeting at at the annual CRUSER TechCon
- A CRUSER News article
- Participation in CRUSER sponsored events
- Contributions to the CRUSER Annual Report
- Providing updated labor plans and budget projections as requested

APPENDIX E: CRUSER LEADERSHIP TEAM

DIRECTOR: Dr. Raymond R. Buettner Jr. is an Associate Professor in the Information Sciences Department at the Navy Postgraduate School and the NPS Director of Field Experimentation. Dr Buettner served 10 years as Naval Nuclear Propulsion Plant Operator while earning his Associate's and Bachelor's degrees. He holds a Master of Science in Systems Engineering degree from the Naval Postgraduate School and a Doctorate degree in Civil and Environmental Engineering from Stanford University. From 2003 to 2005, Dr. Buettner served on the faculty at the Naval Postgraduate School (NPS) and was the Information Operations Chair. He is the Chair of Technical Operations, in which he liaisons between NPS and the Joint Staff J39.He is the Principal Investigator for multiple research projects with budgets exceeding $6 million dollars a year, including the TNT, RELIEF, and JIFX projects. http://faculty.nps.edu/rrbuettn/about.html

DEPUTY DIRECTOR: Dr. Brian Bingham is an Associate Professor in the Mechanical and Aerospace Engineering Department at the Naval Postgraduate School. Dr Bingham received his PhD in mechanical engineering from MIT in 2003. After a brief stint at the Ocean Institute in California, he was appointed to a post-doctoral position at the Woods Hole Oceanographic Institution, Deep Submergence Lab. Dr. Bingham has served as a member of the faculty at the Franklin W. Olin College of Engineering from 2005-2009 and the University of Hawaii at Manoa from 2009-2015. His research is on innovative tools for exploring, understanding and protecting the marine environment. This work includes projects on underwater navigation, autonomous vehicles and sensor integration. http://faculty.nps.edu/vitae/cgi-bin/vita.cgi?p=display_vita&id=1299243456

ASSOCIATE DIRECTOR: Carl Oros, LtCol, USMC (Ret.) is a Faculty Associate - Research and Information Sciences (IS) doctoral student in the Department of Information Sciences. His research and teaching interests include wireless networking, tactical wireless LANs, operator-centric information architectures that support the C2 communication of valuable bits to the lowest tactical level, and biological information. As a Principle Investigator, he has managed several USMC sponsored tactical wireless research projects and has been actively involved in the NPS-USSOCOM Cooperative Field Research Program and the OSD sponsored Joint Interagency Field Experimentation (JIFX) program since 2004. Carl is a retired Marine Corps CH-53E assault support helicopter pilot and holds a Master of Science Degree in Information Technology Management from NPS, a Masters in Military Studies (USMC Command & Staff College), and a BA in Geophysics (Univ. of Chgo). He has been published in the handbook of research on Complex Dynamic Process Management, and the Command & Control Research Program (CCRP) and AFCEA-George Mason University (GMU) Critical Issues in C4 symposia. His current research is focused on the biological aspects of information. http://faculty.nps.edu/vitae/cgi-bin/vita.cgi?p=display_vita&id=1138032442

ASSOCIATE DIRECTOR: Lyla Englehorn, MPP earned a Master of Public Policy degree from the Panetta Institute at CSU Monterey Bay. She looks at issues related to policy in the maritime domain and is involved in a number of projects at the Naval Postgraduate School. Beyond her work with the Consortium for Robotics and Unmanned System Education and Research (CRUSER), she also works with the Warfare Innovation Continuum (WIC), and the NPS Graduate Writing Center. Other work at NPS has included curriculum development and instruction for the International Maritime Security course sequence for the Department of State and NATO.

DIRECTOR EMERTIUS/SENIOR ADVISORY COMMITTEE MEMBER: Jeff Kline, **CAPT, USN (ret.),** is a Professor of Practice in the Operations Research Department at the Navy Postgraduate School and Navy Warfare Development Command Chair of Warfare Innovation. He also is the National Security Institute's Director for Maritime Defense and Security Research Programs. He has over 26 years of extensive naval operational experience including commanding two U.S. Navy ships and serving as Deputy Operations for Commander, Sixth Fleet. In addition to his sea service, Kline spent three years as a Naval Analyst in the Office of the Secretary of Defense. He is a 1992 graduate of the Naval Postgraduate School's Operations Research Program where he earned the Chief of Naval Operations Award for Excellence in Operations Research, and a 1997 distinguished graduate of the National War College. Jeff received his BS in Industrial Engineering from the University of Missouri in 1979. His teaching and research interests are joint campaign analysis and applied analysis in operational planning. His NPS faculty awards include the 2009 American Institute of Aeronautics and Astronautics Homeland Security Award, 2007 Hamming Award for interdisciplinary research, 2007 Wayne E. Meyers Award for Excellence in Systems Engineering Research, and the 2005 Northrop Grumman Award for Excellence in Systems Engineering. He is a member of the Military Operations Research Society and the Institute for Operations Research and Management Science. http://faculty.nps.edu/jekline/

LIST OF FIGURES

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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 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. CRUSER seeks to align efforts, both internal and external to NPS, by facilitating active means of collaboration, providing a portal for information exchange among researchers and educators with collaborative interests, and supporting innovation through directed programs of operational experimentation. This FY14 annual report summarizes CRUSER activities in its fourth year of operation, and highlights future plans.

KEYWORDS: robotics, unmanned systems, autonomy, UxS, UAV, USV, UGV, UUV

POC: Dr. Raymond R. Buettner, Jr.,
CRUSER Director

http://cruser.nps.edu

LIST OF ACRONYMS AND ABBREVIATIONS

This list is not meant to be exhaustive, and includes only the most common acronyms in this report.

A2AD	anti-access area denial (*A2/AD also used*)
ARSENL	Advanced Robotic Systems Engineering Laboratory
ASW	anti-submarine warfare
AUV	Autonomous underwater vehicle
C2	Command and control
C3	Command, control and communications
C4I	Command, control, computers, communications and intelligence
CAVR	NPS Center for Autonomous Vehicle Research
CENETIX	Center for Network Innovation and Experimentation
CEU	Continuing education unit
CNO	Chief of Naval Operations
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
DoD	Department of Defense
DON	Department of the Navy
ISR	Intelligence, surveillance, and reconnaissance
JCA	Joint campaign analysis
JIFX	Joint Interagency Field Exploration
LDUUV	large displacement UUV
MDA	Maritime domain awareness
METOC	Meteorological and oceanographic

MILDEC	Military deception
MIO	Maritime threat detection and interdiction operations
NAVAIR	U.S. Naval Air Systems Command
NAVSEA	U.S. Naval Sea Systems Command
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NWC	Naval War College
ONR	Office of Naval Research
OR	Operations Research Department, NPS
QR	Quick Response (*QR code*)
RAS	robotic and autonomous systmes
ROS	Robot operating system
ROV	Remotely operated vehicle
SEA	Systems Engineering and Analysis (*an NPS curriculum*)
SECDEF	Secretary of Defense
SECNAV	Secretary of the Navy
SME	Subject matter expert
SOF	U.S. Special Operations Forces
SSG	Strategic Studies Group
STEM	Science, technology, engineering, and mathematics
TDA	Tactical decision aid
TechCon	CRUSER Technical Continuum
TNT	Tactical Network Testbed
UAS	Unmanned aerial system

UAV	Unmanned aerial vehicle
UGV	Unmanned ground vehicle
USMC	U.S. Marine Corps
USN	U.S. Navy
USNA	U.S. Naval Academy
USV	Unmanned surface vehicle
USW	Undersea Warfare (*a battle concept and an NPS curriculum*)
UUV	Unmanned undersea vehicle
UxS	Unmanned system
WIC	Warfare Innovation Continuum
WIW	Warfare Innovation Workshop

ACKNOWLEDGMENTS

The CRUSER Director thanks the entire community of interest who joined us since the program inception in March 2011.

The CRUSER Director appreciates the initial support and guidance as well as the continuing interest of Deputy Secretary of Defense the Honorable Robert O. Work.

The CRUSER Director appreciates the continuing support of the current Under Secretary of the Navy, Dr. Janine Davidson.

The CRUSER Director acknowledges the efforts of the CRUSER Advisory Board: RADM Jerry Ellis, USN (ret) NPS Chair of Undersea Warfare; RDML Rick Williams, USN (ret), NPS Chair of Mine Warfare; Dr. J. Paduan, NPS Dean of Research.

The CRUSER Director acknowledges the extraordinary work of the first CRUSER Director, CAPT Jeff Kline, USN (ret.) who continues to serve as an essential advisor to the program.