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Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) FY13 Annual Report, New Directions

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

FY13 Annual Report

New Directions

CRUSER
Consortium for Robotics and Unmanned Systems Education and Research

NAVAL POSTGRADUATE SCHOOL

Compiled by Lyla Englehorn
for Dr. Raymond Buettner, CRUSER Director
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NAVAL POSTGRADUATE SCHOOL

November 2013

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EXECUTIVE SUMMARY

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 seeks to catalyze 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, fostering innovation through directed programs of operational experimentation, and supporting the development of an array of educational ventures.

Chartered to capture a broad array of issues related to emerging unmanned systems (UxS) technologies, CRUSER intends to encompass 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 FY14 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. In February 2013 the CRUSER community of interest reached the 1,000 member mark, and continues to grow. As of 30 September 2013 the CRUSER community of interest included just over 1,160 members from government, academia and industry. This FY13 Annual Report provides a summary of activities during CRUSER's third year of operation and highlights future plans.

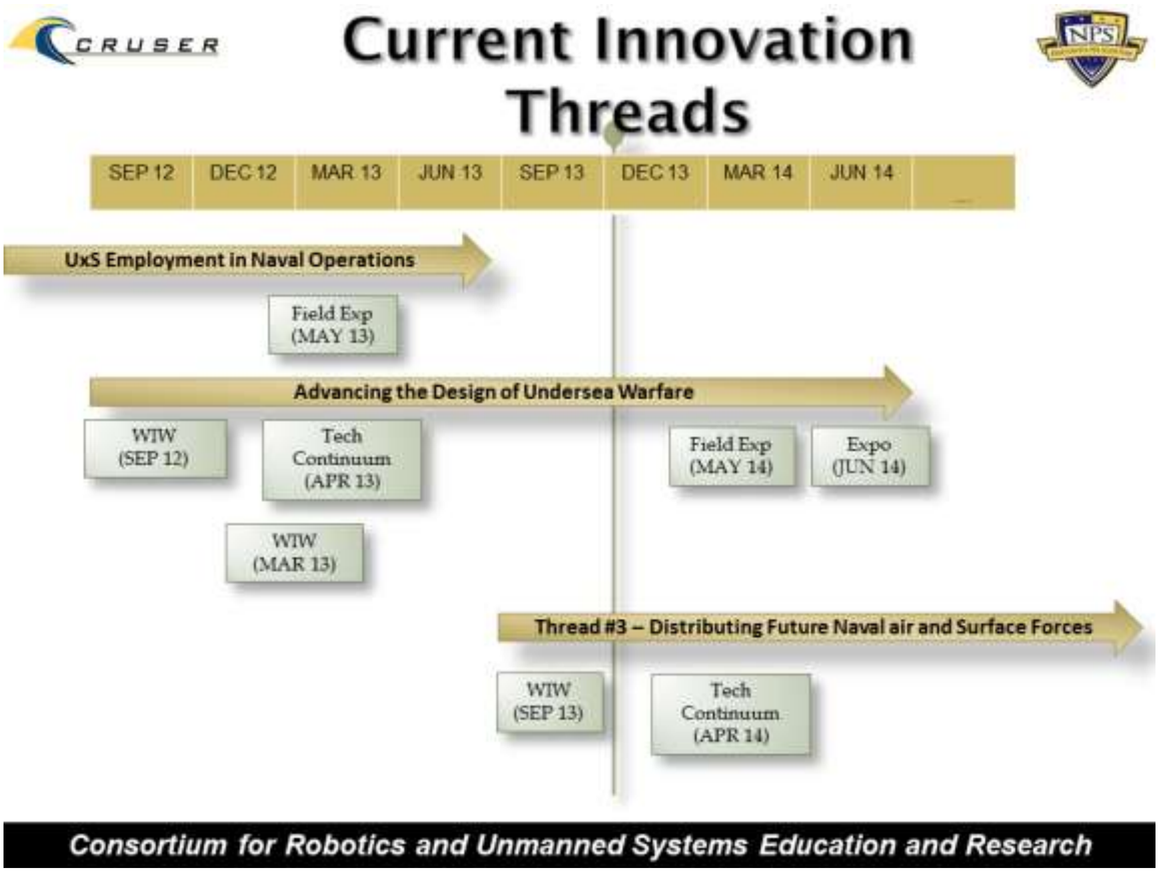

Figure 1. CRUSER program Innovation Threads as of September 2013

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 planned through FY14 include concept generation workshops, technical symposia, and field experimentation to test selected technologies. However, research and education continue to include a broader landscape than just mission areas.

A. VISION

At the direction of 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 and highlighting the educational mission of NPS.

Specific CRUSER goals are to:

- Provide a source for unmanned systems employment concepts for operations and technical research;
- Provide an experimentation program to evaluate 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. Manning requirements, human systems integration, information processing, information display, training, logistics, acquisition, development, command and control (C2) architectures, legal constraints, and levels of autonomy versus mission risk are just a sample of topics for investigation in addition to technical research areas for these systems. These 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 Center for Autonomous Vehicles Research (CAVR), the Center for Network Innovation and Experimentation (CENETIX), and the Seaweb acoustic network. 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, 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.

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 CRUSER 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 continually align with the unmanned systems priorities of the Navy and Marine Corps. The Director reports to the NPS Dean of Research, and will further 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 consisting of the Undersea Warfare Chair, the Intelligence Chair, the Expeditionary and Mine Warfare Chair, and the Assistant Chief of Staff for Aviation Activities. This committee ensures that the fleet and its operations remain a primary consideration in CRUSER activities.

C. NEW DIRECTOR – NEW DIRECTION

Figure 2. Dr. Ray Buettner takes the CRUSER "helm" from CAPT Jeff Kline, USN (ret.), May 2013 (photo by MCSN Danica M. Sirmans)

In May 2013, CRUSER Director Jeff Kline turned over program leadership to Dr. Ray Buettner (*see Figure 2*). From 2003 to 2005, Dr. Buettner served on the faculty at NPS and was the Information Operations Chair. He established himself as one of the nation's foremost experts in the area of influence modeling and in this capacity he was engaged at the direct support of national authorities during the EP-3 collision incident and the post-9/11 response. He also served as the Deputy Director of the Cebrowski Institute for Information Innovation and Superiority. Dr. Buettner then embarked on a period of leave without pay during which he served as founder and Chief Technology Officer for Secure Cognition, Incorporated. He also founded Hybrid Knowledge LLC, a technology and consulting firm. Dr. Buettner returned to NPS in 2007 and has specialized in systems engineering applications, information operations, and field experimentation. He served as the Deputy Director of the Department of Defense's Information Operations Center for Excellence where he focused on graduate education and cyber issues. He teaches in the Information Sciences Department. He is the Chair of Technical Operations, in which he liaisons between NPS and the Joint Staff J38.He is the Principal Investigator for multiple research projects with budgets exceeding $3 million dollars a year, including the TNT, RELIEF, and Joint Interagency Field Exploration (JIFX) projects. The Provost designated Dr. Buettner as the first NPS Director of Field Experimentation in February 2009.

In his first "Director's Corner" statement in the June issue of CRUSER News, Dr. Buettner remarked "In this time of challenging fiscal realities the Department of the Navy's commitment to realizing the operational and economic potential of robotics and unmanned systems is more important than ever. The Naval Postgraduate School, and CRUSER, are important vehicles for realizing these potentials."

D. FY13 PROGRAM ACTIVITY SUMMARY

The CRUSER FY12 Annual Report concluded with a list of proposed FY13 activities. These proposals played out in FY13 to bring Innovation Thread 1 to a successful conclusion, take Thread 2 to the next level, and begin Thread 3:

- CRUSER hosed a second event in the *Robo-Ethics Continuing Education Series* - a continuing education series about legal, social, cultural, and ethical issues for operators, acquisition professionals, and engineers. Although planned to be held in San Diego, California in May 2013 the DoD travel ban necessitated a reschedule to September 2013 on the NPS campus in Monterey. ***This event is detailed in section II.B.1.c of this report.***

- CRUSER continued to sponsor experimentation in FY13 of the most promising technologies from the May 2012 CRUSER Technical Continuum. ***Proposals selected for sponsorship are detailed in section II.D of this report.***
- CRUSER hosted a Technical Continuum (TechCon) for Thread 2 in April 2013 in conjunction with the annual unmanned systems research fair at NPS to demonstrate technologies to aid in the concepts generated the September 2012 Warfare Innovation Workshop (WIW). ***TechCon 2013 is detailed in section II.B.1.a of this report.***
- CRUSER had planned to sponsor a Technical Fair to be held at ONR in June 2013 to demonstrate the results of the first CRUSER Thread. However, the DoD travel ban precluded this effort.
- CRUSER continues to sponsor NPS faculty research and experiments across the holistic topic areas not traditionally sponsored by ONR technical funds such as human resources, human systems integration, concept exploration, and others. ***Selected proposals are detailed in section II.C.1 of this report.***
- CRUSER continued to provide partial funding for the joint ONR/NPS Seaweb at-sea experimentation program with Singapore. ***The MISSION project work is summarized in section II.C.1.k of this report.***
- CRUSER provided a discussion venue for new Navy initiatives. For example, ongoing dialogue between the Naval Postgraduate School, the Naval Academy, and the Naval War College constituting the Navy Robotics Education Continuum provided an opportunity for all three Navy schools to share their unmanned systems curricula to provide better alignment. ***See section II.B.1.d of this report for more details.***
- CRUSER sponsored a WIW in September 2013 to begin CRUSER Innovation Thread 3 exploring distributed future naval air and surface forces. ***See section II.A.1.c for more*** on the "Distributing Naval Surface and Air Force Capabilities" workshop.

- CRUSER continued to fund NPS student travel to participate in research, experimentation. ***Student funded travel is detailed in section II.E.3 of this report.***
- CRUSER continued to add to the community of interest, produce monthly newsletters, and hold monthly community-wide meetings. ***Community of interest outreach and composition is discussed in section II.E.1 of this report.***

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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. The current six year funding expectation for CRUSER is:

FY11	FY12	FY13	FY14	FY15	FY16
$200K	$1.4M	$3M	$5M	$5M	$5M

Activities for each year will be briefed to the Advisory Committee and will receive approval from the sponsor.

FY11 was considered a CRUSER stand up year. With the program's initial funding, CRUSER was established with a Director, Director for Research and Education, Director of Concept Generation and Innovation, and Operations Manager. A CRUSER Community of Interest was established with over 250 members joining from across DoD, academia, and industry within thirty days of the launch of the website (http://CRUSER.nps.edu). An information exchange portal – a "wiki" – was created, and monthly newsletter started. CRUSER aided execution of recurring events such as concept generation workshops, research fairs, and technical gatherings. FY12 was CRUSER's first full year in operation and as a transition year, continued many items started in FY11.

FY13 has taken the established CRUSER program in some new directions. Seed funding was provided to thirteen projects allowing nearly twenty NPS faculty members to start research across many aspects of unmanned systems, including the joint ONR/NPS Seaweb at-sea experimentation program with Singapore (*see report section II:C:1:k*). CRUSER also continued to fund NPS student travel to participate in research and experimentation dealing with all aspects of unmanned systems to help develop the next generation of military officers.

CRUSER is continuing to provide a discussion venue for new Navy unmanned and robotic initiatives. This year CRUSER hosted a debate on lethal autonomous robots (LAR) as part of the Robo-Ethics Continuing Education Series (RECES). The inaugural RECES event was a series of panel discussions for operators, acquisition professionals, and engineers in the Washington D.C. area in coordination with OPNAV N2/6 and ONR. We hope to host a similar event in San Diego once the DoD travel restrictions are lifted.

Specific FY13 objectives were to provide:

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

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

A. CONCEPT GENERATION

1. Warfare Innovation Workshops (WIW)

The first NPS Innovation Seminar supported the CNO sponsored *Leveraging the Undersea Environment* war game 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, and NWC Strategic Studies Group (SSG) Director Fellows.

a. Revolutionary Concept Generation from Evolutionary UxS Technology Changes, September 2011

The Navy Warfare Development Command (NWDC) and CRUSER sponsored WIW was held at NPS in September 2011 in direct support of the SECNAV directive that CRUSER foster the development of unmanned systems concepts to be applied in naval operations. Although the workshop took place during FY11, the results of the CRUSER WIW 2011 were used to inform CRUSER research, symposia, and experimentation throughout FY12 and planning for the future through FY14. The results also serve as an "idea" bank for the entire CRUSER community of interest. Subtitled "*Revolutionary Concept Generation from Evolutionary UxS Technology Changes*," this WIW leveraged the innovation lessons learned in previous workshops and was designed specifically to support concept development for unmanned systems. Participants included NPS students, practicing engineers from Navy labs and industry, and visiting command representatives. They were asked to generate revolutionary concepts using rapidly evolving unmanned naval systems technologies.

Figure 3. CRUSER Director of Research and Education Dr. Timothy Chung (standing at right), with CAPT T. Doorey (USN, ret.), CAPT W. Hughes (USN, ret.), and ADM N. Carr before the CRUSER WIW 2011 final briefs on 22 September 2011

A final report released in October 2011 details the concepts generated by all four teams and presented in their final briefs (*see Figure 3*). From these innovative concepts, the CRUSER leadership team chose five concept areas that warranted further investigation: 1) counter unmanned aerial vehicle (UAV) operations, 2) information assurance, 3) ISR, 4) knowledge management/data management, and 5) non-kinetic strike. CRUSER then invited industry, Navy labs, and academic researchers to demonstrate related technologies at a three day CRUSER Technology Continuum in May 2012.

Two emergent outcomes of the CRUSER WIW 2011 that are not necessarily related to concept generation, but are in line with CRUSER's mandate, were 1) the advancement of general unmanned systems knowledge among the participants; and 2) a greater appreciation for the technical viewpoints for officers, and an operational viewpoint for engineers. The information interchange and relationship building that occurred during this event are characteristic of the WIW venue, and also support CRUSER's overall intent.

b. Advancing the Design of Undersea Warfare, September 2012

Figure 4. September 2012 warfare innovation workshop, "Advancing the Design of Undersea Warfare"

This 2012 WIW was sponsored by NWDC and CRUSER, and was held during the NPS Enrichment Week 17-20 September 2012 to advance the design of undersea warfare and explore unmanned systems contribution to the concept (*see Figure 4*). In direct support of the NWDC Line of Operation in developing the DUSW, CRUSER developed and executed a WIW focused on employment of the undersea warfare operating concept in the War at Sea Strategy. This WIW focused on innovative concept generation for leveraging U.S. strengths in the undersea domain to counter anti-access area denial (A2AD) in Phase 0/1.

The NWDC and CRUSER sponsored workshop was held during the NPS Enrichment Week 17-20 September 2012 to advance the design of undersea warfare and explore the contribution of unmanned systems to the concept. In direct support of the NWDC Line of Operation in developing the *Design for Undersea Warfare* (July 2011), CRUSER developed and executed this WIW focused on employment of the undersea warfare operating concept in the War at Sea Strategy. This WIW focused on innovative concept generation for leveraging U.S. strengths in the undersea domain to counter A2AD in Phase 0/1.

Figure 5. September 2012 Warfare Innovation Workshop participants

Nearly fifty participants (*see Figure 5*) including NPS students from across campus, academia and industry attended. After a morning of orientation to the workshop, the scenario, and approaches to innovation; six teams spent the next two and a half days generating concepts to counter an A2AD threat. Each team concluded the workshop presenting a twenty-five minute brief summarizing their work and sharing their best ideas. From these innovative concepts, several ideas were identified for further research and development. Selected concepts fell into seven distinct categories:

1) **Decoys and military deception (MILDEC):** Designs to obfuscate targeting or cloud the enemy's operational picture – such as an unmanned surface vehicle (USV) swarm fleet or acoustic deception by unmanned systems.

2) **Vessel tagging:** For domain awareness and tracking – such as remora tag with hydro-fan generator.

3) **Non-lethal kinetic effects:** Generation of non-lethal stopping tactics and mechanisms – such as condenser fouling agents.

4) **Undersea positioning, navigation and timing:** For navigation accuracy and domain awareness as an alternative to GPS and surrogate for underwater use.

5) **Undersea "garage":** Autonomous docking, power generation and transfer, deployment and to extend time on station.

6) **Hybrid unmanned vehicles:** Multi-domain vehicles that transition between domains.

7) **Crowd-sourcing:** Leveraging white shipping, regional fishing fleet and other entities to meet mission data collection needs.

Members of the CRUSER community of interest were invited to further develop these concepts at a three day CRUSER UxS Technical Continuum (TechCon) in April 2013 on the NPS campus (see section II.B.1.a). This was the next step along CRUSER's second Innovation Thread.

A final report detailing process and outcomes was distributed to NWDC, NUWC, the NPS Chair of Undersea Warfare, and the CRUSER community of interest. This report is controlled release, and is available upon request (laengleh@nps.edu).

c. Undersea Superiority 2050, March 2013

Figure 6. March 2013 Warfare Innovation Workshop, "Undersea Superiority 2050"

The March 2013 WIW was sponsored by General Dynamics Electric Boat and CRUSER, and was held during the NPS Enrichment Week 25-28 March 2013 (*see Figure 6*).

Figure 7. March 2013 Warfare Innovation Workshop participants

Participants (*see Figure 7*) including NPS students from across campus, academia and industry attended. After a morning of orientation to the workshop, the scenario, and approaches to innovation; four teams spent the next two and a half days generating concepts to counter an A2AD threat. Each team concluded the workshop presenting a twenty-five minute brief summarizing their work and sharing their best ideas. From these innovative concepts, several ideas were identified for further research and development. Selected concepts fell into four distinct categories:

1) **Natural low frequency search methods:** leverage the earth's natural electro-magnetic spectrum for search based on receiving anomalies caused by man- made platforms as they disturb various fields and emissions
2) **Re-seeding energy:** induction transfer of energy to large diameter unmanned underwater vehicle (LDUUV) payload, and LDUUV induction to fielded sensors
3) **Using unmanned underwater vehicles (UUVs) to aid in submarine minefield navigation:** also called undersea "Sled Dogs", or "Cat Whiskers" uses a "dynamic Q route" using Q from the stochastic model
4) **Wide area decoy:** surface launched drone deployment using many inexpensive gliders or "flocks" deployed from LDUUV via a balloon to altitude – add reflectors to confuse adversary

These selected concepts were added to CRUSER's second Innovation Thread, and members of the CRUSER community of interest were invited to further develop these concepts in response to the FY14 Call for Proposals.

A final report detailing process and outcomes was released in May 2013 to a vetted distribution list of leadership and community of interest members. This report is controlled release, and is available upon request (laengleh@nps.edu).

d. Distributed Air and Surface Force Capabilities, September 2013

This NWDC and CRUSER sponsored workshop was held 23-26 September 2013 on the NPS campus. The three and a half day experience allowed NPS students focused interaction with faculty, staff, fleet officers, and visiting engineers from Navy labs and industry; and culminated in a morning of final concept briefs and fruitful discussion of the role of unmanned systems in the future naval force. This workshop also directly supported the SECNAV directive that CRUSER foster the development of actionable operational concepts for unmanned systems within naval warfare areas.

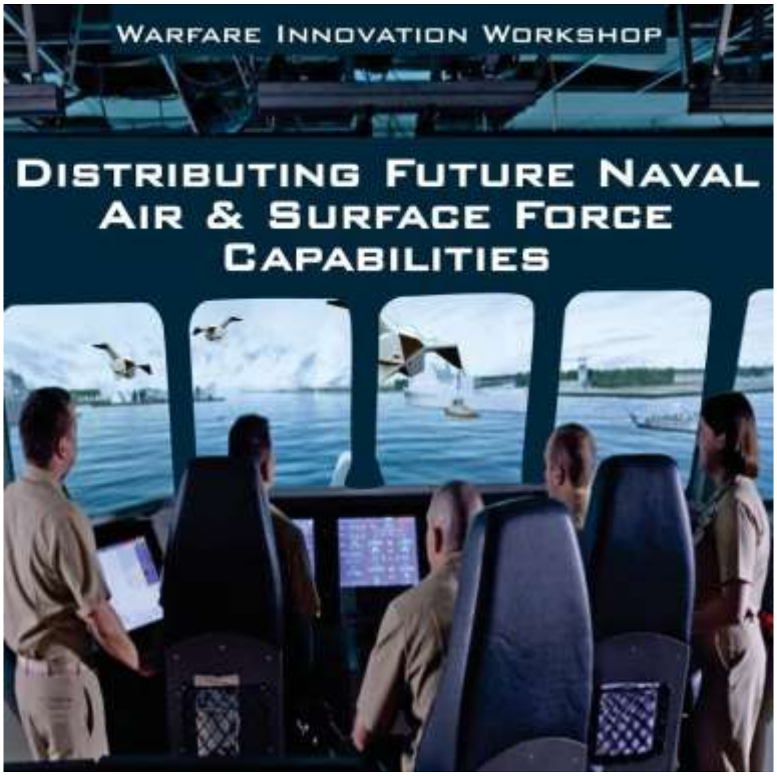


Figure 8. September 2013 Warfare Innovation Workshop, "Distributed Air and Surface Force Capabilities"

The September 2013 workshop, "Distributing Future Naval Air and Surface Force Capabilities," (*see Figure 8*) leveraged the innovation lessons learned in previous workshops and was designed specifically to inspire innovative concept generation. The workshop began with an overview of the scenario followed by a series of knowledge-leveling plenary briefs. The concepts introduced included the distributed air wing, flotilla, and Sea Vex. After lunch, participants listened to a panel discussion on the ethical issues associated with unmanned systems – specifically lethal autonomous robots (LARs). In a final tasking brief, teams were directed to consider modified LCS designs with greater offensive power to integrate with aviation assets, and presented with potential technologies to consider including the long range anti-ship missile (LRASM), the ASW continuous trail unmanned vessel (ACTUV), the tactically exploited return node (TERN), network-optional warfare, and the Hydra concept.

Figure 9. September 2013 Warfare Innovation Workshop participants

Participants (*see Figure 9*) included NPS students from across campus, as well as guests from academia and industry. After a morning knowledge-leveling plenary briefings, the participants attended a panel debate on the ethics of lethal autonomous robots (LAR). Four teams spent the next two days generating concepts to counter an anti-access area denial (A2AD) threat. Each team selected the concepts they chose to present in their final briefs. Following the final briefs on Thursday 26 September 2013, CRUSER leadership identified ideas with potential operational merit that aligned with available resources. These concepts included:

Asset Distribution and Employment Concepts: surface flotilla with expeditionary basing and optionally-manned ships, subsurface flotilla with semi-submersible platforms, distributed expeditionary airbases, dissimilar swarm autonomy, autonomous coordinated UxS maneuvers for sensor positioning, and UAV payloads to augment strike capabilities

C2/3 Concepts: wave-gliders for cueing and C3 networks, virtual crow's nest, full network deployment, leverage ambient signals, C2 for hunter-killer mindset, UAV "Carrier Pigeon," UxS C2 modification, strategic UxS C2, force allocation and employment, biologically encoded acoustic communication , IR "Bat Signal," innovative C3 systems for distributed manned and unmanned platforms and systems

Deception and Weather Concepts: sea chaff or sea flare, disruptive swarm, weather weapons

These selected concepts will begin CRUSER's third Innovation Thread, and members of the CRUSER community of interest will be invited to further develop these concepts in response to the FY14 Call for Proposals. A final report detailing process and outcomes will be released before the end of 2013 to a vetted distribution list of leadership and community of interest members. This report is controlled release, and is available upon request (laengleh@nps.edu).

The CRUSER September 2013 WIW results will also serve as a basis for future CRUSER research and experimentation, as these concepts will begin the third CRUSER programmatic Innovation Thread. Technical members of the CRUSER community of interest will make proposals to test concepts in lab or field environments. Final results of experimentation will be presented to the Office of Naval Research (ONR) in June 2015.

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.

a. Systems Engineering Analysis (SEA) 19A, 2013

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.

Potential adversaries throughout the world continue to acquire and develop sophisticated multilayered, anti-access, area-denial (A2AD) systems. To maintain its maritime superiority, the U.S. must continue to generate systems that are capable of operating successfully in these A2AD environments. In particular, command of the undersea domain remains vital and will increasingly be critical in facing this future battle space.

The challenges the U.S. faces, however, are not limited only to the technological capabilities of the warfighters, but also include a myriad of confounding constraints. In addition to the expected shortfalls of mission-ready assets, the Submarine Forces also must address significant pressures in defense spending. Nevertheless, unmanned undersea vehicles (UUVs) remain one of the top priorities of the Chief of Naval Operations, as UUVs serve as effective force multipliers, while greatly reducing risk, in critical missions in A2AD environments.

The SEA-19A final report presents the findings of analysis and assessment conducted by an integrated systems engineering and analysis team of military officer students at the NPS. Their operationally driven tasking seeks to design a system-of-systems of unmanned and manned undersea vehicles to ensure undersea dominance both in the near term and into the next decade. The importance of the systems perspective to this study is reflected by the extensive engagement with many operational stakeholders, academic researchers, industry partners, and acquisitions programs across the Naval enterprise. The capability-based approach highlights the mission suitability of both currently fielded UUVs and also technologies realizable within the next decade. The capstone final report summarizes these critical insights and provides detailed recommendations to inform decision makers of the present to prepare for the undersea forces of the future.

Ongoing research in the field of unmanned technologies led to the following 2013 Systems Engineering Analysis project tasking:

> *Design a system of Unmanned Undersea Vehicles (UUVs) that will provide an operational undersea force available for tasking over a range of missions by 2024. Consider current fleet structure and funded UUV programs as the baseline system of systems to conduct current missions. Include in your analyses attributes of the vehicles, payloads, projected costs, possible mission sets, and concepts of operations. The system may be a totally unmanned force or a combination force of manned platforms and unmanned undersea vehicles that can execute missions*

in an integrated fashion. A full range of alternatives should be considered. Of major importance in successfully deploying such a capability in the desired timeframe is acquisition strategy and DOTMLPF execution.

In response to this tasking given by the Deputy Director for Warfare Integration and the Executive Director of Submarine Forces, the SEA-19A project team recommends the following sustained UUV force structure:

- 26 Large Displacement UUVs (LDUUVs)
- 120 Recoverable 21 inch UUVs
- 121 Expendable 21 inch UUVs

Total lifecycle cost for the proposed UUV fleet over its 20-year program is $3.65B (in FY13 dollars). This conservative estimate accounts for the entire lifecycle, including procurement, continuous operations, maintenance, and training.

Four high-level decision drivers, based on the extensive concept generation modeling, simulation, analysis, lead to the above recommended UUV force structure:

1) UUVs are essential to maintaining undersea dominance. Increased operational capability and reduced risk for personnel and high value platforms are provided by unmanned systems. UUVs provide greater operational reach to both subsurface and surface manned combatants.

2) Employment of multiple UUVs provides a significant increase in successful mission accomplishment.

3) Utilization of expendable UUV variants provides unique capabilities and cost savings, especially for missions where probability of survival is low, or there is no need to recover the UUV.

4) An appropriate balance of critical unmanned capabilities is required for effective mission performance. All UUVs must have the capability to maneuver, survive, and persist in challenging environments. However, the cost vs. benefit analysis of advanced mission functionality often shows

negligible gains in mission success, at a relatively disproportionate increase in cost.

Using a systems engineering methodology, SEA-19A addresses problems related to increasingly complex anti-access area denial (A2AD) environments. These environments require stealthy vehicles to execute critical mission sets. Stakeholder, functional, and mission-based analyses lead to the selection of the following four missions for inclusion in the proposed 2024 A2AD UUV concept of operations:

1) Intelligence, Surveillance, and Reconnaissance (ISR)
2) Information Operations (IO)
3) Mine Countermeasures (MCM)
4) Offensive Attack Operations (including ASW, ASUW, and offensive mining)

These operations are assessed to be the most likely missions that benefit in the near-term from UUV technologies by 2024. These assessments are based upon current programs of record and technology readiness levels across the Navy, and in industry and academia.

LDUUVs are a critical component of the proposed force structure due to the inherent capabilities of larger and more capable sensors, greater payloads, and longer endurance. Specifically, LDUUVs are required for persistent ISR and various offensive attack operations, but face operational and cost effectiveness constraints Only 60 inch diameter and smaller LDUUVs are included in the analysis due to the operational constraints of the Universal Launch and Recovery Module in development for the Virginia Payload Module. To provide maximum operational flexibility, the Littoral Combat Ships are assessed to be feasible launch and recovery platforms for LDUUVs of this size.

Twenty-one inch and smaller diameter UUVs provide substantial capability for all proposed missions. The 21 inch UUVs are capable of being launched from all manned platforms, with the size only being constrained by current torpedo tube diameters. This effectively turns any manned platform into a UUV launch and recovery vessel. Analysis also shows that significant cost savings can be realized by designing several 21 inch variants as exclusively expendable.

Robust autonomous collision avoidance capabilities are key technology enablers which are necessary to reduce unanticipated UUV losses due to circumstances such as grounding and entanglement in fishing nets. Continued research needs to be conducted to develop innovative ways to overcome these operational issues. Until these technologies mature, the employment of multiple UUVs in squads provides an advantageous solution to maintain acceptable probabilities of mission success. This concept factors significantly into the proposed force structure.

To maintain the proposed sustained UUV force levels over the projected 20-year period, a total of 35 LDUUVs, 167 21 inch Recoverable UUVs, 440 21 inch Expendable UUVs are to be procured. The proposed acquisition strategy accounts for operational and training losses, while maintaining sufficient force levels for large-scale maritime battlespace preparation in an A2AD environment.

The SEA 19A full report is available at:

http://www.nps.edu/Academics/Programs/SEA/subpages/projects/2013Spring.html

POC: Dr. Timothy Chung (thchung@nps.edu)

b. Search Theory and Detection (OA3602), Winter 2013

Students in this course, Search Theory and Detection (OA3602) investigated the operational applications of probability modeling, stochastic processes, optimization, statistical analysis, and decision making as applied to the theory of search. Topics included:

- Characterization of detection devices
- Use and interpretation of sweep widths and lateral range curves
- Models of surveillance fields, barriers, tracking and trailing
- Measures of effectiveness of search-detection systems

- Allocation of search efforts
- Sequential search
- Introduction to the statistical theory of signal detection

The increase in information-gathering and target search tasks using unmanned systems has facilitated a resurgence of analytic models for efficient search, requiring operational analysis of sensor capabilities, theoretical bounds on performance, and probabilistic models for search performance. Relevant applications include use of unmanned systems for anti-submarine warfare, search and rescue, intelligence, surveillance, and reconnaissance.

POC: Dr. Timothy Chung (thchung@nps.edu)

c. Joint Campaign Analysis (OA4602), Winter and Summer 2013

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. This academic year students provided quantitative assessment to DARPA's TERN program (long range UAV) to support small combatants and furthered development in unmanned distributed air wing capabilities for Navy Warfare Development Command's concept generation branch.

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

d. Advanced Applied Physics Lab (PC4015), Winter and Summer 2013

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 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 RM Harkins (rharkins@nps.edu)

e. Combat Survivability (ME4751), Winter and Summer 2013

This course provides the student with an understanding of the essential elements in the study of survivability, reliability and systems safety engineering for military platforms including submarines, surface ships, fixed-wing and rotary wing aircraft, as well as missiles, unmanned vehicles and satellites. Technologies for increasing survivability and methodologies for assessing the probability of survival in a hostile (non-nuclear) environment from conventional and directed energy weapons will be presented. Several in-depth studies of the survivability various vehicles will give the student practical knowledge in the design of battle-ready platforms and weapons. An introduction to reliability and system safety engineering examines system and subsystem failure in a non-hostile environment. Safety analyses (hazard analysis, fault-tree analysis, and component redundancy design), safety criteria and life cycle considerations are presented with applications to aircraft maintenance, repair and retirement strategies, along with the mathematical foundations of statistical sampling, set theory, probability modeling and probability distribution functions.

POC: Christopher Adams (caadams@nps.edu)

f. Policies and Problems in C4I (CC4913), Spring 2013

The class project for this course focused on designing a C2 system for Navy missile boat and coastal patrol boat operations to support South China Sea allies in an A2AD environment, with no satellite uplink capability. The scenario used small unmanned aircraft in a carrier-pigeon role to facilitate boat-to-boat communications in that communications-denied environment. The class project report is a PowerPoint presentation complete with speaker's notes.

POC: Dr. Dan Boger (dboger@nps.edu)

B. EDUCATION

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, catalog degree programs, short courses, and certificate programs. CRUSER's education work also involves surveying and aligning curricula for interdisciplinary unmanned systems education.

The Navy Robotics Education Continuum, launched in FY12, will ensure unmanned systems curriculum alignment across Navy academia. The broad areas of unmanned systems and robotics span not only diverse disciplines but also diverse operational perspectives. As such, the educational approaches necessarily encompass the core foundations of robotic systems at undergraduate levels, deeper understanding of capabilities, technologies, and consequences at graduate levels, and awareness of broader impacts of policy and decision-making at professional levels. The collection of these perspectives represent the spectrum of education related to unmanned systems and robotics for our current and future military leaders, and the CRUSER Navy and Marine Corps UxS Education Continuum aims to capture these efforts and assist in aligning them across the U.S. Naval Academy, the Naval Postgraduate School, and the Naval War College.

In FY13 the Continuum continued to engage, and increased interaction between USNA, NWC, and NPS students, faculty and researchers. NPS developed a solid relationship with the USNA Weapons and Systems Engineering Department, and NPS also interacted with the NWC through their Alfa Halsey war gaming project.

An initial effort to catalog degree programs, short courses, and certificate programs throughout the U.S. was also started in FY13, and will continue into FY14. Ongoing education efforts include plans to create short course programs as identified by community of interest, and to align curricula for interdisciplinary autonomous systems education across the NPS campus and throughout DoD academia. A catalog of unmanned systems related courses at all three institutions is being populated using the CRUSER

wiki tool at:

https://wiki.nps.edu/display/CRUSER/Navy+Robotics+Education+Continuum.

1. Education Initiatives

The CRUSER Technical Continuum (TechCon) 2013 and the 3rd Annual Robots in the Roses research fair led the CRUSER education efforts in FY13. Education initiatives in FY13 also included the second event in the CRUSER Robo-Ethics Continuing Education Series (RECES), and sponsorship of four USNA Summer block internships at NPS.

a. CRUSER Technology Continuum (TechCon), April 2013

Figure 10. CRUSER Technical Continuum (TechCon), April 2013

NPS CRUSER held its second annual Technical Continuum (TechCon) from 9 – 11 April 2013 (*see Figure 10*). This event was for NPS students and faculty interested in education, experimentation and research related to employing unmanned systems in operational environments. Presentations were not meant to present or propose research to demonstrate the entire concept for advancing the design of undersea warfare, but rather highlight specific important elements to show the concept's feasibility.

Table 1. CRUSER Technical Continuum presentations, April 2013

TOPIC	SPEAKER
Navy Data Oriented ISR Concepts	RDML Jan E. Tighe, NPS Interim President
Developing an Undersea "Garage" for Persistent AUF Operations in Monterey Bay	Mr. Sean Kragelund, NPS CAVR
Challenges of Small Maritime Craft Tagging and Tracking: cyber distortion and multi-platform taggin	Dr. Alex Bordetsky, NPS
Automated Position Uncertainty Management for Submarine Navigation in GPS-Denied Environments	LT Ryan Hilger, NPS

UAS Implementation of Full-Motion Video: spectral imaging for real-time signature-based ISR and decision making	Mr. Alan Jaeger, NPS Center for Asymmetric Warfare
Maritime In Situ Sensing Inter-Operable Networks involving Acoustic Communications in the Singapore Strait	Professor Joe Rice
Preliminary Requirements, and Systems Engineering Plan for an Unmanned Autonomous Surface Craft (UASC) modeled after the U.S. Navy Landing Craft Utility	Mr. Montrell Smith, NPS
Using Small Unmanned Aerial Vehicles for Undersea Warfare	Dr. Peter Guest, NPS
Foundations for DoD's Policy on Autonomy	Mr. Paul Siegrist, N2/N6F2
Develop Total Ownership Cost (TOC) and Schedule Estimates for the Transition and Integration of Synthetic Aperture Sonar as a module in the MK 18 MOD 2 UUV system	Dr. Dan Nussbaum, NPS
Exploring Technical, Operational, and Ethical Challenges related to the Autonomous System Support to the Tactical Marine	Professor Scott Miller and Dr. Dan Boger, NPS
A Long Endurance Hybrid Air, Land, Water Vehicle	Professor Kevin Jones and Dr. Vladimir Dobrokhodov
Countering Adversarial Unmanned Systems	Dr. Timothy Chung, NPS
A Collaborative Robotic Diver Assistant for Underwater Operations	Dr. Noel Du Toit, NPS CAVR
Surveillance and Tracking by Autonomous Underwater Gliders	Professor Kevin Smith, NPS
Establishing Long-Term Presence in Monterey Bay using NPS "Wave Glider" USV #2 from Liquid Robotics	Dr. Don Brutzman, Dr. George Lucas and Dr. Duane Davis, NPS
A Systems Engineering Approach to the Future of Unmanned Undersea Warfare	NPS Systems Engineering Analysis Cohort 19 Alpha

TechCon 2013 was intended to further concepts developed during the September 2012 Warfare Innovation Workshop and showcase NPS student and faculty work in advancing undersea operations capabilities. Seven distinct concepts were selected from those presented at the September 2012 Warfare Innovation Workshop, but they are broad enough to include a host of specific research questions. For example, non-lethal stopping concepts using a hardening gel that block ship board heat exchangers when ingested from under the hull. Exemplar topics like this support both material science (can we create such a gel?) to legal and ethical questions. Selected concepts included:

1) **Decoys and military deception (MILDEC):** Designs to obfuscate targeting or cloud the enemy's operational picture – such as a USV swarm fleet or acoustic deception by unmanned systems.
2) **Vessel tagging:** For domain awareness and tracking – such as remora tag with hydro-fan generator.
3) **Non-lethal kinetic effects:** Generation of non-lethal stopping tactics and mechanisms – such as condenser fouling agents.
4) **Undersea positioning, navigation and timing:** For navigation accuracy and domain awareness as an alternative to GPS and surrogate for underwater use.
5) **Undersea "garage":** Autonomous docking, power generation and transfer, deployment and to extend time on station.
6) **Hybrid unmanned vehicles:** Multi-domain vehicles that transition between domains.
7) **Crowd-sourcing:** Leveraging white shipping, regional fishing fleet and other entities to meet mission data collection needs.

TechCon 2013 was held in the NPS Center for Autonomous Vehicle Research (CAVR) space in the basement of Halligan Hall. Presentations covered on-going student and faculty research, as well as proposals for CRUSER FY14 funding in research related to unmanned systems and the undersea domain. The NPS CRUSER TechCon 2013 was unclassified.

TechCon 2013 concluded with the Third Annual Robots in the Roses Research Fair starting at 1500 on Thursday, 11 April, on the Quad and Spruance Plaza.

b. 3rd Annual Robots in the Roses Research Fair, April 2013

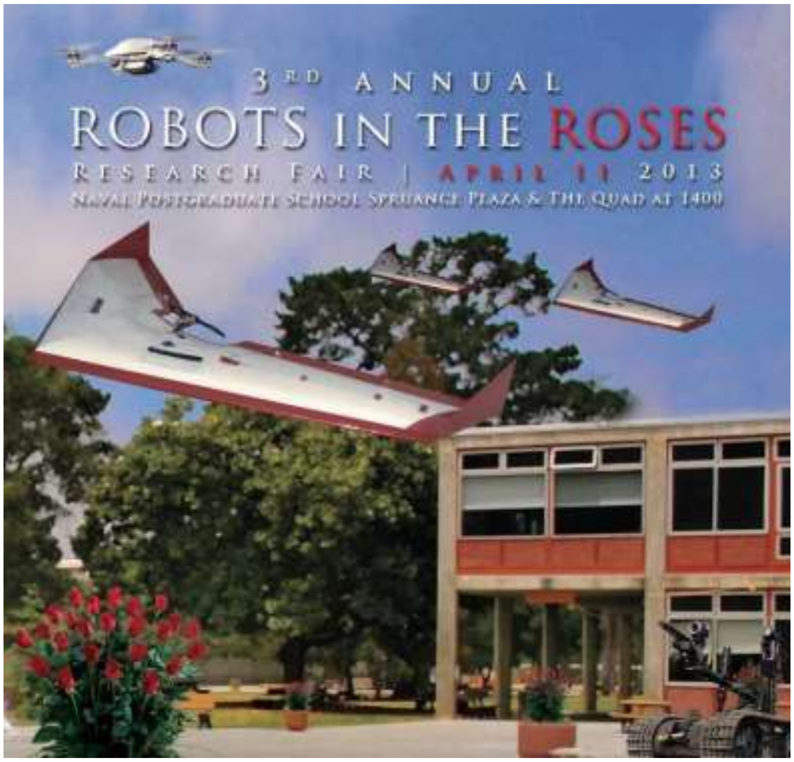


Figure 11. Robots in the Roses Research Fair, April 2013

Each year, CRUSER hosts a research fair highlighting unmanned systems activity on the NPS campus. The primary mission of this third annual research fair (*see Figure 11*) was again to offer the CRUSER community of interest an opportunity to share research and educational opportunities in the areas of unmanned and robotic systems. 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. The welcome address this year was given by RDML Jan E. Tighe, NPS President. Local press was in attendance, and the research fair was on the front page of both The Monterey Herald and The Californian newspapers the following day.

c. Continuing Education: Robo-Ethics, September 2013

The primary event in FY13 for continuing education was the Robo-Ethics Continuing Education Series (RECES) 2013 panel debate on lethal autonomy (*see Figure 12*).

Figure 12. Robo-Ethics Continuing Education Series (RECES) 2013 panelists, (*left to right*) Joshua Foust, Dr. Bradely Strawser, and Dr. Heather Roff

NPS Department of Defense Analysis Assistant Professor Bradley J. Strawser moderated a debate between Visiting Associate Professor Heather M. Roff with the University of Denver and freelance journalist Joshua Foust. The debaters sought to answer the question, "Does the future of unmanned and autonomous weapons pose greater potential ethical dangers or potential ethical rewards?"

Roff, whose writings have been critical of unmanned combat systems, is the author of "Killing in War: Responsibility, Liability and Lethal Autonomous Robots," which was featured in the *Routledge Handbook for Ethics and War* (2013). Foust's work has appeared in The Atlantic, New York Times and Foreign Policy, amongst other publications, and he is a frequent guest on BBC World News. He is also the author of "A Liberal Case for Drones," an article in the May 2013 issue of Foreign Policy magazine. He takes a more favorable view of unmanned systems and has argued that, under limited conditions, they are an ethical, even preferable option to boots on the ground. Strawser is himself an authority on the ethics of unmanned systems. He came to NPS last year after working with Oxford University's Institute for Ethics, Law and Armed Conflict. His work, "Killing by Remote Control: The Ethics of an Unmanned Military" explores the potential ethical pitfalls and gains that unmanned systems pose.

Figure 13. Robo-ethics panelists discussing autonomous systems, September 2013

This discussion (*see Figure 13*) was embedded in the first day of the NWDC/CRUSER Warfare Innovation Workshop on Monday 23 September 2013. Archival videos of their presentations and resulting discussion are available for viewing at https://www.nps.edu/Research/cruser/roboethics.html .

Although CRUSER did not bring any speakers directly to the NPS campus in FY13, the program did promote other presentations on campus and in the greater Monterey County region. A particular effort of note was CRUSER participation in the Monterey Bay Aquarium Research Institute (MBARI) speaker series in Moss Landing.

d. CRUSER Scholars and STEM Outreach

FY13 saw the realization of the CRUSER Scholar program, bringing four U.S. Naval Academy midshipmen to campus for four weeks to work with NPS faculty on robotics research and experimentation. When asked to comment on the benefit of the CRUSER Scholar experience, USNA Midshipman Daniel Fallon said, "Being exposed to the different technologies here gives us an idea on how we can collaborate with other projects, like the quadrotor drone, which also has its own camera. Not only do we meet the engineers and subject matter experts for these cutting-edge tools, it's a chance for them to poke holes and find strengths and weaknesses in what we are attempting to do with our own project.” The USNA interns project work included:

- Optimal trajectory generation for USVs (Seafox)
- Leveraging open source robotics software for low coast autonomous USV operations
- Integration and implementation of QR Codes for passive optical communications

CRUSER also brought high school, undergraduate and graduate level interns to campus through the NREIP and SEAP programs. In FY13, 17 interns were able to do robotics project work through the NREIP program, and several more were able to come to campus through the SEAP program.

CRUSER efforts continue to support of the nationwide initiative to increase student exposure to fields of study and subsequent careers in science, technology, engineering and math. CRUSER leverages the simple fact that robots are cool as a catalyst to engage students at a visceral level. Once engaged, student interest in STEM pursuits is more easily nurtured.

Other CRUSER STEM activities in FY13 included subject matter expert input for regional science fairs, working as a liaison for robotics mentoring of local high school robotics clubs, and developing a relationship with the Engineering Department at neighboring Monterey Peninsula Community College. We also included a STEM activity for the K-6 students at our 3rd Annual Robots in the Roses research fair (*see Figure 14*).

Figure 14. Luis Villegas of the Presidio of Monterey helps Allison Friefeld, 12, of Carmel Middle School with a remote operated vehicle she built, April 2013 (photo by Vern Fisher)

The "Build Your Own ROV" activity was presented in partnership with the local chapter of Marine Advanced Technology Education (MATE).

2. NPS Student Theses

The primary mission of NPS is to educate members of the armed forces. CRUSER community of interest members guided several NPS students as they developed and completed their thesis work throughout the CRUSER program lifetime (*included in iterative listing in Appendix C*). In FY13, over twenty NPS students completed unmanned systems related thesis or project work with the support of CRUSER. Although not an inclusive list, students mentored in FY13 include:

Table 2. FY13 CRUSER mentored NPS student theses (*alphabetical by author*)

Thesis project title/subject:	NPS Student (s)	
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	Maj Matthew T. Taranto,	FY13

aircraft mishaps	USAF	
A systems engineering analysis of unmanned maritime systems for U.S. Coast Guard missions	LT James B. Zorn, USCG	FY13

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 using the wiki tool at https://wiki.nps.edu/display/CRUSER/Potential+Thesis+Topics.

C. RESEARCH

At the direction of the SECNAV, NPS continues to leverage long-standing experience and expertise in the research and education of robotics and Unmanned systems to support the Navy's mission. CRUSER was established to serve as a vehicle by which to align currently disparate research efforts across the NPS campus as well as among our academic partners and greater community of interest.

1. FY13 CRUSER Funded Research

In March 2012, CRUSER made its second call for proposals to seed research topics. The stated funding period was 31 October 2012 through September 2013, and the funding levels were set at $75,000 to $125,000 per proposal. Researchers were asked to submit proposals in one of the following general subject areas:

- **Technical:** Power, Sensors, Controls, Communications, Architectures, Human Factors, Information Processing and Dissemination
- **Organization and Employment:** Human Capital Requirements, Risk Analysis, Force Transition, Acquisition, Policy, Concept Generation evaluation and Authorities
- **Social, Cultural, Political, Ethical and Legal**
- **Experimentation**
- **Defense against threat unmanned capabilities**

Due at the beginning of August 2012, 35 proposals totaling more than $3.3 million in requests were submitted for CRUSER funding. The CRUSER advisory committee selected a dozen projects to receive $1.3 million in total to support their work in FY13 (*see Table 3*).

Table 3. FY13 CRUSER funded research projects

PRINCIPAL INVESTIGATOR(S)	PROJECT TITLE
Bordetsky	Networked Unmanned Systems Formation for Rapid Detection, Interdiction, and expert Reach-back in Maritime Interdiction Operations (MIO)
Brutzman	Improving Novel Approaches using Ultra-high Resolution 60p Full Motion Video Cameras for QR Code Exploitation in Field Conditions
Chu	Incorporation of Navy’s Ocean Data into UUV Path Planning with Obstacle Avoidance
Chung	Countering Adversarial Unmanned Systems: Live-Fly Experimentation With Aerial Combat Swarms
Colosi	Support for NPS Seaglider Operations
Du Toit	A Collaborative Diver Assistant for Underwater Operations
Guest, Guest, Frederickson, Murphree	The Use of Unmanned Systems for Environmental Sampling and Enhance Battlespace Awareness in Support of Naval Operations
Hatch	Comparative Analysis of X-47 UCAS and F-18 Squadron Manpower
Jones, Dobrokhodov, Kaminer	Tactical Long Endurance Unmanned Air System (TaLEUAS)
Jones	UAS Training and Pilot Certification Program
Millar	Experimental Unmanned Aircraft System (UAS) Interim Flight Clearances
Rice	MISSION

a. Networked Unmanned Systems Formation for Rapid Detection, Interdiction, and expert Reach-back in Maritime Interdiction Operations (MIO)

The major goal for the conducted research was to explore solutions for advancing integrated detection and interdiction of maritime transfers of illicit materials, based on the synergy between ad hoc, mobile, network-enabled groups of unmanned systems and platforms. The experimentation effort was concentrated on integration of unmanned ground vehicles (UGVs) in maritime threat detection and interdiction operations (MIO) action as the least among unmanned buoy systems (UBS), and unmanned surface vehicles (USV) studied platform for MIO.

The research resulted in unique lessons learned and understanding of operational constraints, which will enhance MIO capabilities through the employment of ubiquitously networked unmanned systems.

(a) Methodology

In order to address the task, we:

1. Conducted field experimentation by leveraging the existing MIO testbed environment, emerging tactical networks, mobile sensors, UGVs, and instantaneous reach-back to remote subject matter experts (SME), collectively providing multiple system threat adjudication and autonomous unmanned sensor systems guidance.

2. Captured lessons learned regarding emergent UGV formation based MIO concepts of operations into a shared knowledge base.

Table 4. Models explored/generated from MIO experimentation

Operational Model	Integrated Detection Model	2007	2008	2009	2010	2011	2012	2013
Search Large Vessel	BTs employ active/passive handheld nuc/rad sensors, collect biometric data, feed live-video, use small UGVs to enhance search operations on large vessels	X	X	X	X	X	X	X
FP/ Oil Platform Security	Model search & detection at an oil rig/large platform, with manual and UGV-mounted sensors							X

Novel aspects of network-enabled, integrated detection and interdiction models were evaluated. In the UGV application model, two types of UGVs were used in the experiment. A stand-off radiation and nuclear detection capable UGV was used by the boarding team to augment rapid exploitation and illicit material search on the main deck of a large vessel or oil platform structure (*see Figure 15*).

Figure 15. Modeling oil rig/large vessel protection

A small throwable UGV was used in formation with large sensor carrying UGV to help the boarding team provide video surveillance evidence on hidden areas during the vessel search

Experimentation occurred from 11-13 June 2013, at the approximate locations shown in the table below (*see Table 5*). It has been conducted as Phase V of globally distributed effort for learning new techniques in countering illicit radioactive or nuclear material transfer threat detection and interdiction within the framework of protecting large vessel or oil rig from the improvised radioactive or nuclear device explosion.

Table 5. MIO field trials, FY13

	2013	(M) 10 Jun	(T) 11 Jun	(W) 12 Jun	(R) 13 Jun
LOC		***SF Bay***			
Phase			**Ph IV**	**Ph V**	**Ph IV/V**
Trials	**Action**	***Set up***	***Field Trials***		
	AM	Trials Coordination & Training	Small Craft D&I	**Lg Ship Search (w/UGVs)**	Small Craft D&I
	PM		Building D&I	Hotwash / Planning	**Large Ship Search (W/UGVs)**

Table 6. Experiment plan and description for large vessel (oil/gas rig platform protection w/networked UGVs)

Short Title	Large Craft (Oil/Gas Rig) Platform Protection w/Networked UGVs
Phase	Ph V
Operational Problem	Remote oil platforms and related infrastructure are “soft” targets to terrorist threats. A relatively small incident can have catastrophic environmental and economic effects. Small boat attack team, supported by the insider in the oil rig crew, could set up dirty rad/nuc and chemical sources in the perimeter and inner areas of the large platform. The Boarding Team needs to find the sources and develop the maximal level of threat awareness through the network enabled search and rapid site exploitation. The process should be augmented by unmanned detection/surveillance systems and networked divers.
Research Questions	1. Is continuing networking between the RB Experts and Boarding Team members, searching the decks and interior feasible, what performance constraints are associated with it?” 2. How efficient is integration of UGV in the process of searching and stand-off detection across the decks and in the interior areas?
Objectives	1. Integrate surface and subsurface sensors into a common C2 to provide early threat warnings to key responses to protect personnel and infrastructure and buy time for response forces to arrive. 2. Share tagging, tracking, nuc/rad alerts, and SSE (analysis) data with CWIX, DTRA SW, and DNDO JCCAS command posts 3. Integrate unmanned system based (UGV) detection and surveillance in the rapid platform search process 4. Enable RB SME access to UGV/BT surveillance and detection data feeds 5. Integrate collaboration with networked divers in the platform perimeter search
Partner Interest Area	• Scalable Maritime Asset Response to Terrorist Threats (SMARTT), Rapid VBSS information sharing with SMEs (C3PO), • *Integrating different detection and tracking devices over ATAK mesh and reach-back networks* • Integrating unmanned platforms in source search and detection • Networking with divers during the search/detection process
Shared Data Elements, Application Flows	• ***TRACKS*** - Transmit boarding team members, unmanned detector platform, and diver location into the COP. • ***IMAGE/SPECTRA UPLOADS***:

	-Transmit detection results - Transmit biometric forensics using US/NATO SSE kit; transmit via ATAK & Wave Relay radios -Transmit detection and SE info into the VBSS support C3PO system • ***TEXT CHAT*** -Annotate rad/nuc and chemical detection results in form of Observer Notepad entries Boarding Team and RB SMEs -Annotate SSE info from ATAK-WR nodes in form of Observer Notepad entries
Integration Variables	1. ATAK ad hoc mobile (MANET) routing 2. Cellular coverage 3. Satellite posting delays 4. Baseline SA event (tracks, alerts-NPS) CoT XML file format transfer to Atlascraft Targtr, DNDO N.25, DTRA SW, and CWIX (Appendix…) formats
Expert Reach-back (RB) Model	1. Adapt NATO ACT/ JCBRNE CoE expert RB schema # 3 (JCBRN CoE diagrams in Appendix….) 2. In case of two-way degraded networking, apply RB schema #2 (see Annex K, App 3) 3. Use C3PO portal for Boarding Team reporting on the events encountered (Appendix 4 to Annex K) 4. Conduct stand-off detection during the search of decks and interior using following the steps in NATO SACT schema (Appendix 1 to Annex H)
Constraints	1. Transmitting from obstructed environment inside hold of ship 2. Very short discrete time windows for stand-off detection, SSE feed submission 3. Lack of 4G/LTE coverage en route 4. MANET IP space routing incongruences 5. Communicating with divers via submerged RF access point operating on 2.4GHz band (near-field comms in up to a half of feet range)

Criteria	1. Delays or discrepancies in position postings 2. Frequency distribution for Operator-RBSME messaging 3. Weight (centrality) of problem defining terms in CBRN unit-SOF, Boarding Team-Divers, and Boarding Team-RBSME dialogs
Location	**SF Bay, Alameda Pier**
Date	**12, 13 June**
Players	Red/Blue Team (NORSOF) Red/Blue Team (US SOF) CBRN RBSMEs (JCBRN CoE) SSE RBSMEs (SSE Cell)
MIO Testbed Infrastructure	• MARAD Large Vessel, USS ADM Callaghan • Testbed mesh networked SF Bay Marine Police rad/nuc sensor boats • Testbed tactical MANET (NPS MIO and ATAK IP spaces), tagging, and sensor nodes (Appendix 2 diagrams) • Testbed globally distributed RBSME sites (Annex K, App 2 diagrams) • NPS SA and data capture tools • C3PO • SOF, CWIX, DTRA SW, DNDO JCCAS, CRDC observer sites
Local Test Bed Components in Use	• ATAK units (4ea) • nuc/rad Riids/Sensors • SSE Kit • Source Materials
Scenario	The target small craft, previously released by patrol crews conducting stand-off primary and secondary screening of possible shielded source, appeared to be having rendezvous with the large platform. Subsequent third screening and crew SSE, as combined with new SSE results of searching the affiliate's site in SF, indicate an imminent threat to the platform, the remotely controlled source and explosives could've been setup in and around it. An immediate rapid search of the main deck, interior areas, and platform perimeter is needed.
Operational	1. The Blue Team comprised for collective learning purposes of 10thSFG,

Model	CANSOF, NPS, and SFPD CBRN operators, starts searching the main deck and interior of the platform. 2. All Blue Team members are communicating between them and out, using wearable ATAK mesh network (they become the mobile nodes of it). 3. One part of the Blue Team is conducting rapid search of the upper deck and SSE using the UGV platform to augment stand-off rad/nuc and explosive detection. 4. Based on the SSE results and RB SME feedback the second part of Blue Team is exploring the interior using the Throwbot, small throw able UGV, capable of providing video surveillance on hidden difficult to access areas 5. Concurrently NORSOF and SFPD divers are searching the perimeter of the platform for possible attached (floating) parasite device communicating to TOC via submerged RF Access Point.			
Phase Sequence	**Activity**	**PDST**	**Zulu (GMT)**	**CET**
	Prep, Move to test location	(0700-0745)	(1400-1445)	(1600-1645)
	Obj # 1.1 (Track Data)	same		
	Obj # 1.2 (R/NSensor Data)	(0830-1400)	(1530-2100)	(1730-2300)
	Obj # 2.1 (R/N RBSME Collaborat'n)	(0830-1300)	(1530-2000)	(1730-2300)
	Obj # 1.3 (SSE Data)	"	"	"
	Obj # 2.2 (SSE RBSME Collaborat'n)	"	"	"
	Hotwash	Upon completion		
Task 1.1	***Transmit track data into mesh network***			
	MoPs	**Data Collector**		
	a) **Track data** feeds into mesh network	DC# 1,6		
	b) Mesh **network flow supports** track data transmissions	DC# 5		
	c) Data is received **accurate**	DC# 3		
Task 1.2	***Transmit sensor data & supporting info into mesh network***			
	MoPs	**Data Collector**		
	a) **Equipment feeds data/info** into mesh network	DC# 1		
	b) Mesh **network flow supports** data transmissions	DC# 5		
	c) Data is received **accurate**	DC# 3		

Task 1.3	***Transmit forensic/biometric (SSE) data & supporting info into mesh network***		
	MoPs		**Data Collector**
	a) **Equipment feeds data/info** into mesh network		DC# 1
	b) Mesh **network flow supports** data transmissions		DC# 5
	c) Data is received **accurate**		DC# 4
Task 2.1, 2.2	**Collaborate (Operators and RB SMEs) to adjudicate**		
	MoPs		**Data Collector**
	a) Mesh network supports **Data** collaboration		DC# 6
	b) " **VoIP** "		DC# 6
	c) " **Video** "		DC# 6
	d) " **Chat** "		DC# 6
	e) " **Whiteboard** "		DC# 6
Data Collection	**Network Logs**	• System Latency (yes/no, DTG)	DC# 5
	Tech Obsns	• Network **S/W** issues • Network **H/W** issues • RSE/Sensor **equipment** issues	DC# 1,6 DC# 6 DC# 1,6
	Player Survey	• User perceptions of network **QoS** • User perceptions of **collaboration tools** • User perceptions of **cyber-distortion**	DC# 1,6 DC# 1,3,6 DC# 5 (Hudgens)
	Obsr Notepad	• Soft copy capture of each **text chat thread**	DC#5
	White board	• Soft copy capture of **Elluminate session**	DC#5
	SA View	• Periodic screen captures of SA View **COP**	DC#5
	DCs	DC #1 - SOF Team POC DC #2 - MOC (Bydgoszcz) DC #3 - R/N RBSME (JCBRN CoE) DC #4 - SSE RBSME (JFTC NOC) DC #5 - NPS NOC DC #6 - Principal Investigator / White Team	

(b) Execution

Research questions addressed in the experiment were:

1) *Is continuing networking between the RB Experts and Boarding Team members, searching the decks and interior feasible with the help of an Unmanned Systems formation? What performance constraints are associated with it?"*

2) *How efficient is integration of UGV in the process of searching and stand-off detection across the decks and in the interior areas?*

Figure 16. Suspect craft carrying illicit radioactive or nuclear explosive materials underway to rendezvous with the large vessel

The experiment started with tracking a small suspect tagged craft carrying illicit RND/explosive material, which appeared to be underway to rendezvous with the large vessel in the port area (*see Figure 16*). The yellow track pictured below (*see Figure 17 yellow track*) shows the improvised radiological or nuclear device (IRND) threat delivery to the area of large vessel.

Figure 17. Delivery of IRND (*yellow track*), and two SOF teams (*blue tracks*) arrive to search the vessel and to eliminate threat

The search party (*see Figure 17 blue track*) of two coalition SOF teams equipped with UGVs and sensors is underway to find and interdict the threat (*see Figure 18*).

Figure 18. SOF teams aboard patrol boats en route search and interdict target

While on the move in high speed patrol boats, SOF crews share the received threat delivery tracks and identify the location of the search area onboard a large vessel/oil rig structure. Upon getting close to the target area prior to boarding, they deploy a networked subsurface diver (*see Figure 19*) and throw small video surveillance UGV[1] on the main deck of the large vessel (*see Figures 20 and 21*).

Figure 19. Deploying diver and UGVs

[1] Throwbot from Recon Robotics

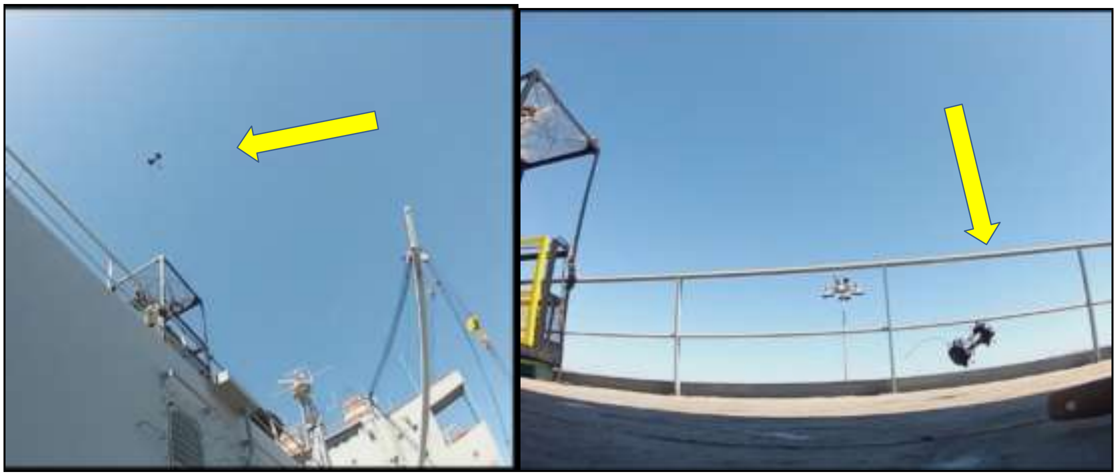


Figure 20. Throwbot being deployed

Figure 21. Throwbot scanning the main deck

To speed up the search process the Throwbot is then thrown downstairs providing video surveillance on the hidden area (*see Figures 22 and 23*).

Figure 22. Deploying Throwbot to lower deck

Figure 23. Video display from the Throwbot

At the same time a large UGV is deployed by the BT to scout the main deck for the IRND (*see Figures 24-26*).

Figure 24. UGV equipped with detector and network

Figure 25. Network controlled UGV deploys

Figure 26. UGV is steered from cargo compartment to upper deck

The partnering SOF teams step aboard and establish the boarding team ad hoc mesh network via the wearable nodes (*see Figure 27*), sponsored by the 10thSFG hosts for the experiment. The UGVs and BT members are now sharing data on findings and are communicating seamlessly with the reach-back experts in the remote locations.

Figure 27. Wearable BT-UGV crew, reach-back networking

The alerts are starting to come. The UGV based radioactive or nuclear sensor indicates a threat presence in the area. However, the sensor doesn't have a directional capability, so the exact location is not known yet. While the direct action team (NORSOF) is operating the vehicle, the CANSOF expert on site communicates with remote analysts and makes his own decision pointing the UGV in the right direction based on the rapid spectra analysis (*see Figure 28*).

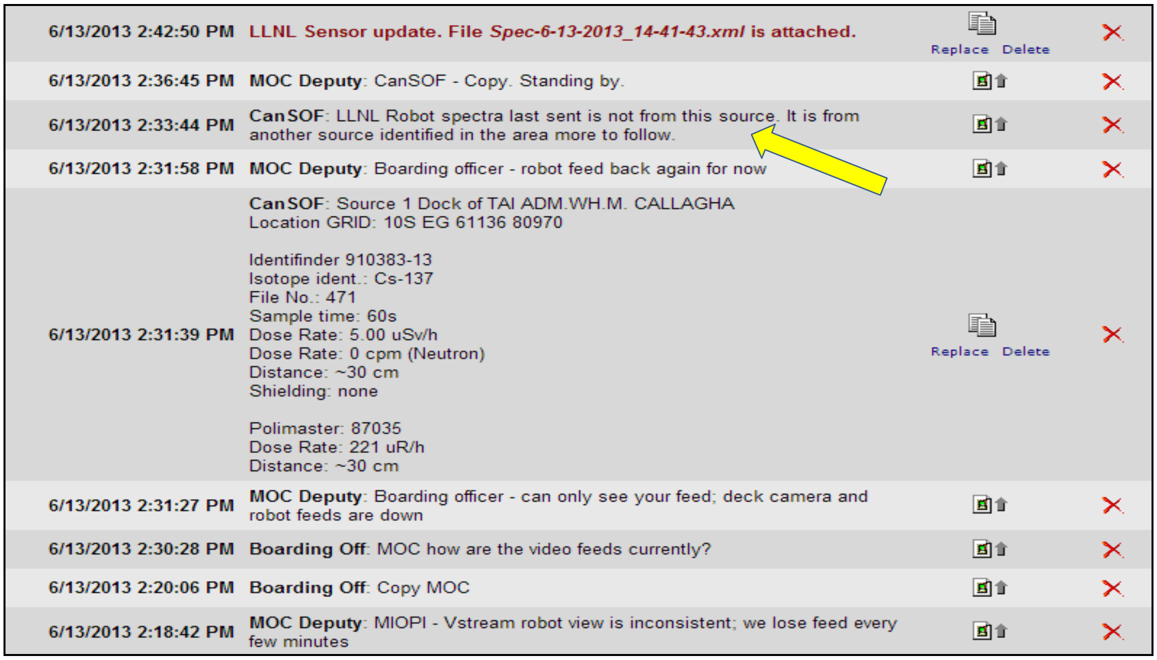
6/13/2013 2:18:42 PM	**MOC Deputy**: MIOPI - Vstream robot view is inconsistent; we lose feed every few minutes	
6/13/2013 2:13:21 PM	**LLNL Sensor update. File *Spec-6-13-2013_14-13-14.xml* is attached.**	Replace Delete
6/13/2013 2:11:21 PM	**MOC Deputy**: Copy boarding officer.	
6/13/2013 2:07:15 PM	**Boarding Off**: currently robot and handheld being operated through collaboration of norsof and cansof teams.	
6/13/2013 1:58:43 PM	**CanSOF**: Dock of TAI ADM.WH.M. CALLAGHAN Spectra sent LLNL Robot Location GRID: 10S EG 61136 80970 Identifinder 910383-13 Isotope ident.: n/a File No.: n/a Sample time: n/a Dose Rate: .001 mR/h Dose Rate: 0 cpm (Neutron) Distance: n/a Shielding: none Polimaster 87035 Dose Rate: 1 uR/h Distance: n/a	
6/13/2013 1:55:46 PM	**LLNL Sensor update. File *Spec-6-13-2013_13-55-40.xml* is attached.**	Replace Delete
6/13/2013 1:55:34 PM	**MOC Deputy**: Confirming all video streams up and clear - deck (VC1), boarding officer (VC1), robot (videostream)	
6/13/2013 1:54:40 PM	**LLNL Sensor update. File *Spec-6-13-2013_13-54-37.xml* is attached.**	Replace Delete
6/13/2013 1:49:50 PM	**MOC Deputy**: MIOPI - Lost videostream from robot	
6/13/2013 1:45:26 PM	**MOC Deputy**: MIOPI - Confirming robot view in VC1 and video streaming. Audio coming through reasonably clear, but with echo.	
6/13/2013 1:43:19 PM	**MIOPI**: NOR AND CAN TEAMS IN PLACE	

Figure 28. SOF teams collaborate on driving and guiding UGV

It is a new technique, which partnering SOF teams are learning (*see Figure 29*).

Figure 29. Maneuvering UGV from sensor readings

The captured dialogue (*see Figure 30*) illustrates the team's adaptation to handling the UGV and analyzing sensor results. The line in red, starting with "LLNL…." represents an alert generated by the sensor on board the UGV, which is posted to the Boarding Team collaborative. You can see CANSOF adding on another layer of situational on source finding in the line marked by "2:33:44 PM".



6/13/2013 2:42:50 PM	**LLNL Sensor update. File *Spec-6-13-2013_14-41-43.xml* is attached.**	Replace Delete
6/13/2013 2:36:45 PM	**MOC Deputy**: CanSOF - Copy. Standing by.	
6/13/2013 2:33:44 PM	**CanSOF**: LLNL Robot spectra last sent is not from this source. It is from another source identified in the area more to follow.	
6/13/2013 2:31:58 PM	**MOC Deputy**: Boarding officer - robot feed back again for now	
6/13/2013 2:31:39 PM	**CanSOF**: Source 1 Dock of TAI ADM.WH.M. CALLAGHA Location GRID: 10S EG 61136 80970 Identifinder 910383-13 Isotope ident.: Cs-137 File No.: 471 Sample time: 60s Dose Rate: 5.00 uSv/h Dose Rate: 0 cpm (Neutron) Distance: ~30 cm Shielding: none Polimaster: 87035 Dose Rate: 221 uR/h Distance: ~30 cm	Replace Delete
6/13/2013 2:31:27 PM	**MOC Deputy**: Boarding officer - can only see your feed; deck camera and robot feeds are down	
6/13/2013 2:30:28 PM	**Boarding Off**: MOC how are the video feeds currently?	
6/13/2013 2:20:06 PM	**Boarding Off**: Copy MOC	
6/13/2013 2:18:42 PM	**MOC Deputy**: MIOPI - Vstream robot view is inconsistent; we lose feed every few minutes	

Figure 30. Adapting to UGV based threat sensing

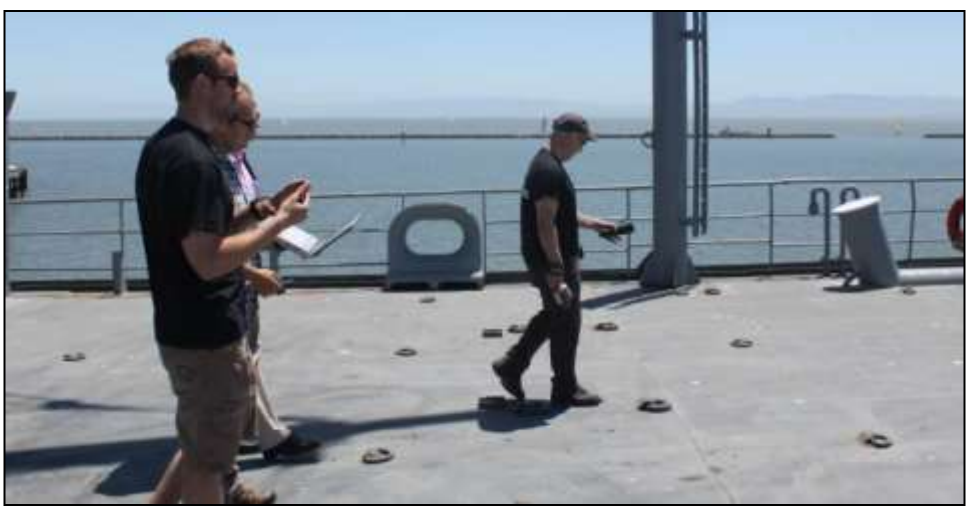
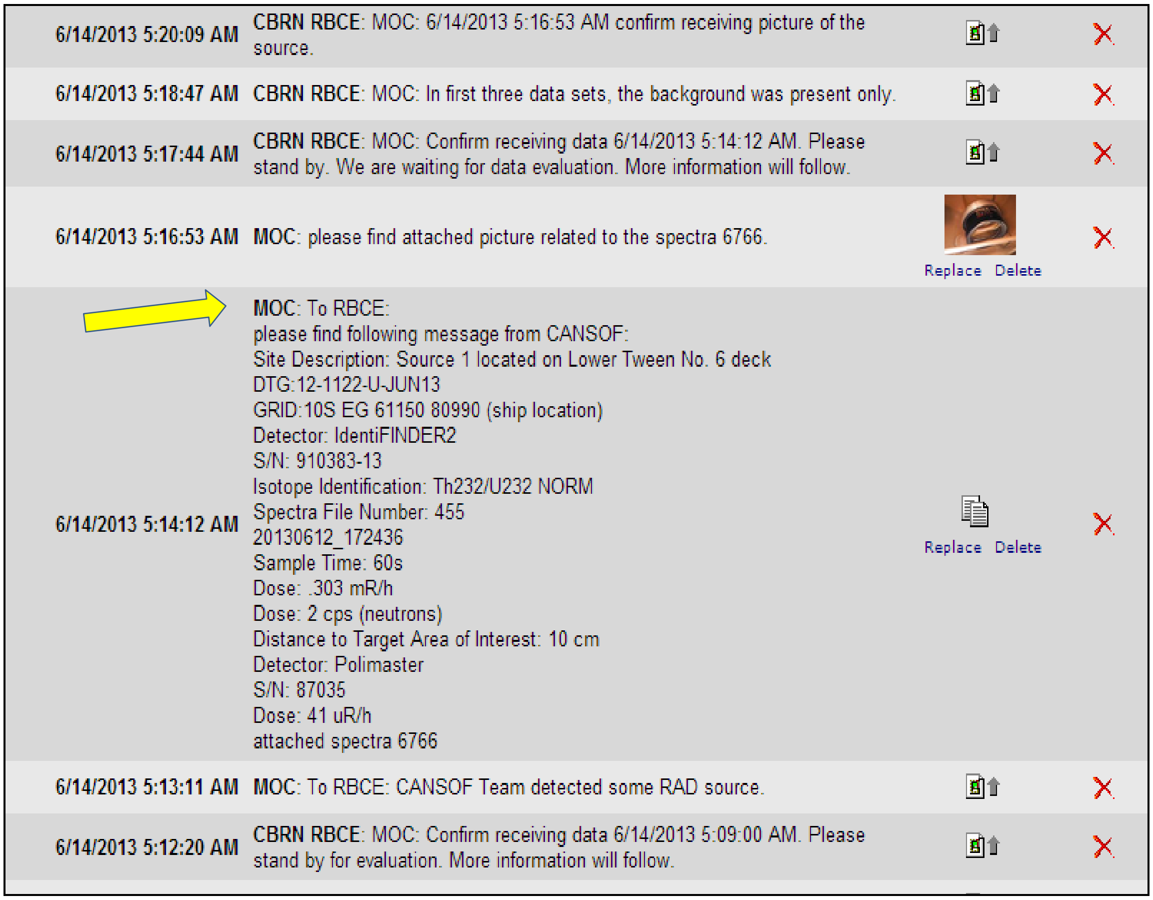


Figure 31. Simulating additional small UGV with a sensor



6/14/2013 5:20:09 AM	**CBRN RBCE**: MOC: 6/14/2013 5:16:53 AM confirm receiving picture of the source.		
6/14/2013 5:18:47 AM	**CBRN RBCE**: MOC: In first three data sets, the background was present only.		
6/14/2013 5:17:44 AM	**CBRN RBCE**: MOC: Confirm receiving data 6/14/2013 5:14:12 AM. Please stand by. We are waiting for data evaluation. More information will follow.		
6/14/2013 5:16:53 AM	**MOC**: please find attached picture related to the spectra 6766.	Replace Delete	
6/14/2013 5:14:12 AM	**MOC**: To RBCE: please find following message from CANSOF: Site Description: Source 1 located on Lower Tween No. 6 deck DTG:12-1122-U-JUN13 GRID:10S EG 61150 80990 (ship location) Detector: IdentiFINDER2 S/N: 910383-13 Isotope Identification: Th232/U232 NORM Spectra File Number: 455 20130612_172436 Sample Time: 60s Dose: .303 mR/h Dose: 2 cps (neutrons) Distance to Target Area of Interest: 10 cm Detector: Polimaster S/N: 87035 Dose: 41 uR/h attached spectra 6766	Replace Delete	
6/14/2013 5:13:11 AM	**MOC**: To RBCE: CANSOF Team detected some RAD source.		
6/14/2013 5:12:20 AM	**CBRN RBCE**: MOC: Confirm receiving data 6/14/2013 5:09:00 AM. Please stand by for evaluation. More information will follow.		

Figure 32. Direction to source has been found. Note the line marked with the "5:16:53" time stamp, which contains the actual shielded source identification

Based on the CANSOF guidance and large UGV sensing the final result was achieved (*see Figure 32*) by the human operator adding small UGV simulation functionality (*see Figure 31*). Using formation of UGVs and manned-unmanned teaming (*see Figure 33*) appeared to be very critical to the mission's success.

Figure 33. Manned and unmanned teaming

(c) Conclusions

Continued networking between the reach-back experts and boarding team members, and searching the decks and interior are feasible with the help of an unmanned systems formation (*see Table 7*). However, the FY13 work illustrated that it requires human adaptation and learning of new roles. Integration of UGV in the process of searching and stand-off detection across the decks and in the interior areas significantly improves the boarding team's performance, providing additional autonomous capability in remote areas. It is most efficient for generating initial alerts. Locating the parasite box/materials requires human deployment on-site and action by the formation.

Table 7. Evaluation of mesh network and data collection results

Short Title	**Large Craft (Oil/Gas Rig) Platform Protection w/Networked UGVs**	
Phase	**Ph V**	
Task 1.1	***Transmit track data into mesh network***	
	a) UGV & Boarding Team **Track data** feeds to mesh network	Success
	b) Mesh **network flow supports** track data transmissions	Success
	c) Data is received **accurate**	Partial
Task 1.2	***UGV Transmits sensor data & supporting info into mesh network***	
	a) **UGV feeds data/info** into mesh network	Success
	b) Mesh **network flow supports** data transmissions	Success

	c) Data is received **accurate**	Success
Task 1.3	***Transmit forensic/biometric (SSE) data & supporting info into mesh network***	
	a) **Equipment feeds data/info** into mesh network	Success
	b) Mesh **network flow supports** data transmissions	Success
	c) Data is received **accurate**	Success
Task 2.1, 2.2	**Collaborate (Operators and RB SMEs) to adjudicate**	
	a) Wearable Mesh network supports **Data** collaboration	Success
	b) Wearable Mesh network supports **UGV Control**	Success
	c) Mesh network supports **Video** collaboration	Success
	d) Mesh network supports **Chat** collaboration	Success
	e) Mesh network supports **Whiteboard** collaboration	Not Tested

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

b. Improving Novel Approaches using Ultra-high Resolution 60p Full Motion Video Cameras for QR Code Exploitation in Field Conditions

Over the last several decades, the U.S. Navy's ability to communicate visually has atrophied to the point where it can no longer be relied upon in critical tactical scenarios. Visual communications, such as flag semaphore and flashing light, have been replaced by radio communications and have become the standard for operations today. The drawback to these radio communications is that they can be used to geolocate forces, they can be intercepted and they can be interrupted. Quick response (QR) codes introduce a method for communications that has the potential to reinvigorate visual communications and restore a measure of security to tactical operations. QR codes are two-dimensional barcodes that have the ability to represent significantly more information than traditional one-dimensional barcodes (*see Figure 34*). Further, they inherently contain an error correction capability of up to 30% of the encoded data.

Figure 34. QR code painted on top of King Hall, Naval Postgraduate School (description available at http://qr.nps.edu)

CRUSER-sponsored research has developed a data flow representing the end-to-end steps required for the transmission of data via QR code from a sender to a recipient. Of the items in the data flow, the most significant barriers to success are the environmental effects associated with large ranges. As range increases, superior technologies are required to overcome environmental effects and capture an image of a QR code with sufficient detail for decoding. To date, the maximum successful range for a QR code transmission has been 750 yards using an Astro 4K studio camera with a 580 mm lens. Potentially readable images were captured in intervals up to 2000 yards, but at these large ranges, optical turbulence and visibility prevented successful scanning without significant image enhancement. With further research, this technology can have a significant impact on naval communications. Tactical units can establish a secure channel during routine operations, such as formation steaming, well-deck operations, and replenishment at sea, while maintaining radio silence. QR codes can to help the fleet restore its emissions control (EMCON) proficiency in a time when vulnerability to electronic attack is at an all-time high. Improvements with communications when under the restrictions of Hazards of Electromagnetic Radiation to Ordnance (HERO) are also possible. An unexpected area for future work emerged from these studies – the use of a digital flashing light system leveraging existing technologies for visual communication.

Key to potential fleet use is NPS implementation of an initial tactical decision aid (TDA) that provides end-users a simple interface for sending and receiving QR code communications. It takes into account all factors end-to-end and is streamlined to be injected directly into traditional communications channels replacing the RF link. Development of this TDA has produced a basic interface using open source QR code libraries and has demonstrated the ability to encode, send, receive, and decode messages. Further development will incorporate optical means for QR code transmission.

The CRUSER sponsored QR Code research in FY13 involved several NPS students. Both LT Stephen Richter and LCDR Andrew Lucas completed complementary theses investigating both the technical and the tactical aspects of QR code signaling (*see section II.B.2*). The figure below (*see Figure 35*) is a result of their work.

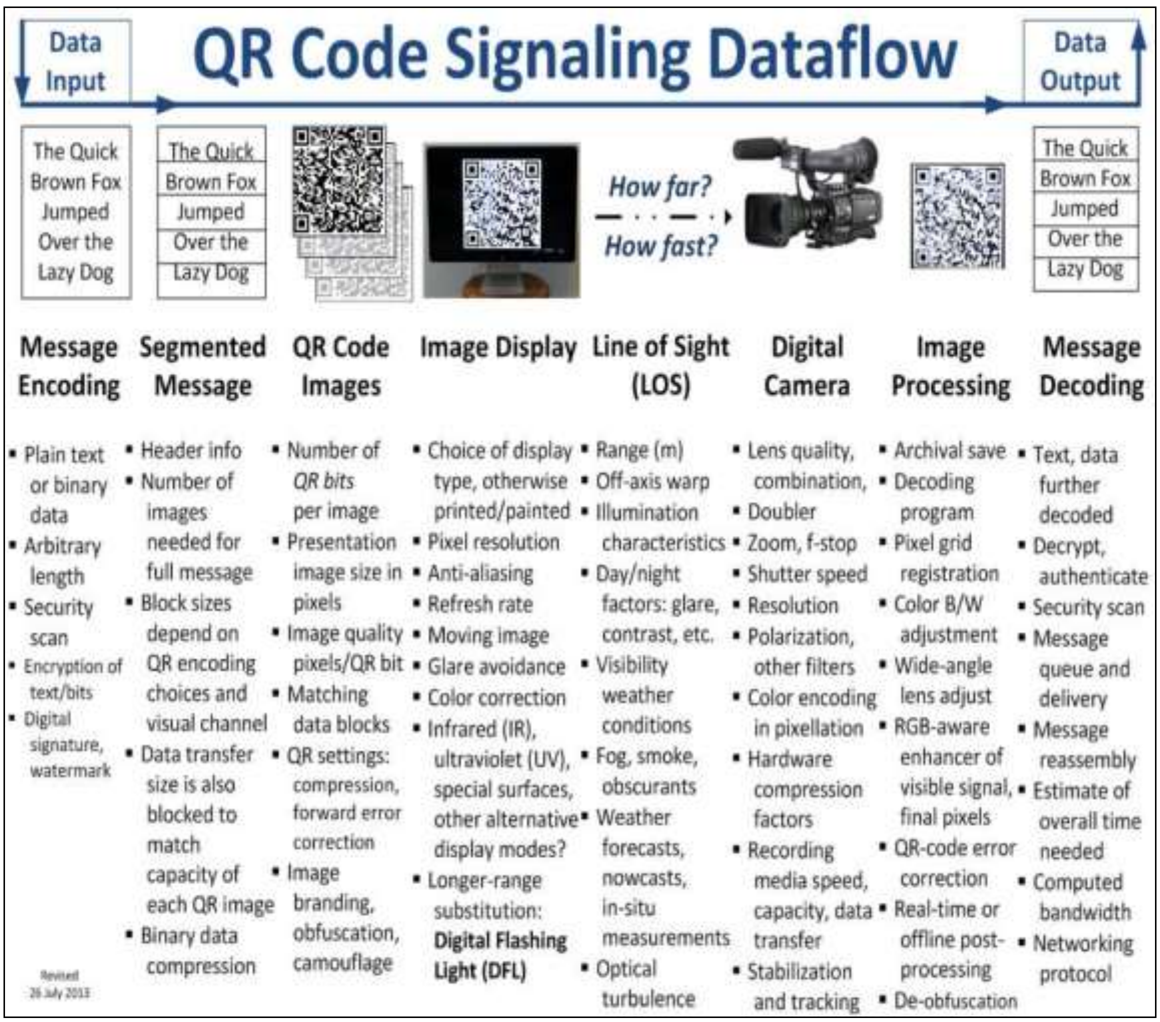


Figure 35. QR code signaling creates a full-fledged communications data channel.

Numerous areas of future work are now evident and necessary. Some has already begun. U.S. Naval Academy (USNA) Midshipmen Jonathan Driesslein and Daniel Fallon worked with NPS Associate Professor Don Brutzman, technical director in the Modeling, Virtual Environments and Simulation Institute (MOVES), on QR Code experimentation in July and August 2013. Work on campus included using a projector to allow the webcams on their laptops to read QR (quick response) codes in a chat environment (*see Figure 36*). Funded by CRUSER, this open-source Java software was created and is maintained at NPS. Text typed from their keyboards created a unique QR representation and is read by the camera scan at real-time speeds. Serving as their mentor, Dr. Brutzman and the students demonstrated the tool at the NPS Joint Interagency Field Exploration (JIFX) exercise at Camp Roberts in August 2013.

Figure 36. USNA Midshipmen Jonathan Driesslein and Daniel Fallon experimenting with quick response (QR) code communications, July 2013 (video demonstration available at http://qr.nps.edu)

"One of the many ways QR codes can help in emission control is to relay the code through light as we did with ship-to-ship signaling. However, now the QR code represents hundreds of characters and with the use of stronger LED lights, and flashing much more rapidly, messages can be relayed without radio emissions," Dr. Brutzman explains. This work also has implications for reducing the risks associated with HERO.

POC: Dr. Don Brutzman (brutzman@nps.navy.mil)

c. Incorporation of Navy's Ocean Data into UUV Path Planning with Obstacle Avoidance

The primary objective of this research is to develop new methods and algorithms for optimal UUV path planning with incorporating real-time ocean data. This multi-year project is jointly funded by the CRUSER ($85,344) and the Naval Oceanographic Office (NAVO) ($120,000) in FY13. Four NPS METOC students (all U.S. Navy) have been working on the project for their MS degrees with participation of scientists as co-advisors with inter-disciplinary backgrounds from multi-institutions: Peter Chu (Oceanography, NPS), RADM Jerry Ellis (ASW Chair Professor, NPS), Ronald Bestch (Mine Warfare, NAVO), Frank Bub (Ocean Modeling and Prediction, NAVO), and Peter Fleischer (Sedimentology, NAVO). The major task in FY13 is to develop effective schemes for processing near-real time high resolution ocean data such as drifting robotic probes (Argo profiling floats) and global drifter array, and obtaining streamfunction from the processed real ocean data. The ongoing effort is to incorporate the real-time ocean data into the UUV path planning (modest request for FY14 funding). Two students have completed their theses in March and June 2013. Two theses will be completed in December 2013. All of them will be published in scientific journals and presented in national and international conferences. Four NPS theses produced from this project are:

- LCDR Paul Kutia, "Intelligence fused Oceanography for ASW using Unmanned Underwater Vehicles (UUV)" (Secret). MS in Meteorology and Oceanography, March 2013.
- LT Thai Phung, "Analysis of Bioluminescence and Optical Variability in the Arabian Gulf and Gulf of Oman for Naval Operations" (Restricted). MS in Meteorology and Oceanography, June 2013.
- LT James Fritz, "Computer Aided Mine Detection Algorithm for Tactical Unmanned Aerial Vehicle (TUAV)", MS in Meteorology and Oceanography, December 2013
- LT Mary Doty, "Analysis of Ocean Variability in the South China Sea for Naval Operations" MS in Meteorology and Oceanography, December 2013.

Advanced UUV path planning is to determine the optimal path between starting position to goal position with avoidance of obstacles. The path planning algorithm can be divided into pregenerative and reactive types. The first type algorithms determine the path prior to the mission, which makes the path difficult to change. The second type algorithms employ various computational methods to correct the path as UUV moves. Usually, the potential (φ) method is commonly used in the UUV path planning with analytical (hypothetical) ocean velocity being taken for computing φ. We divided this project into three parts: (1) development of a streamfunction (ψ) method with analytical ocean velocity and comparison between the potential and streamfunction method, (2) development of the optimal spectral decomposition (OSD) algorithm to process the real time ocean data from global surface drifter array and Argo drifters, and (3) development of an algorithm to compute potential (φ) and streamfunction (ψ) from the real time ocean data.

We developed the streamfunction based algorithm (*see Figure 37*) for UUV path planning. This method contains specific requirement of the UUV maneuverability in the irrotational flow field with constrained sonar (*see Figure 38*) for modification of stream function and numerical techniques. This method is less affected by local minima than classical potential method. The stream function method for single and multiple obstacles in the two dimensions were studied with constrained searching space and the detailed parameters conditions. The simulation results confirm that this method is feasible and suitable for UUV. In this part of work, the flow field was assumed irrotational and incompressible (not for the real ocean),

$$\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y}, \quad \frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x} \tag{1}$$

and the analytical flow field is used

$$\omega = \phi + \mathrm{i}\psi = f(z) + \bar{f}\left(\frac{r^2}{z-b} + \bar{b}\right). \tag{2}$$

Algorithm 1: Stream function based path planning algorithm

z = a;
while $z \neq b$ **do**
  for $l \leftarrow 1$ **to** l_s **do**
    for $\theta_t \leftarrow \theta_h - \theta_s$ **to** $\theta_h + \theta_s$ **do**
      for $\theta \leftarrow \theta_t - \theta_c$ **to** $\theta_t + \theta_c$ **do**
        $f_{cost}(\theta_t) = \psi_s(x + l\cos\theta + \mathrm{i}(y + l\sin\theta))$
      end
    end
  end
  $\theta_h = \min_\theta f_{cost}(\theta)$
  $z = x + l_m \cos\theta_h + \mathrm{i}(y + l_m \sin\theta_h)$
end

Figure 37. Streamfunction based path planning algorithm

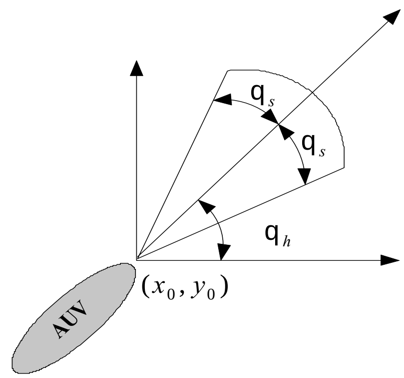


Figure 38. Fan-shaped area of sonar propagation

With the analytical flow field (2), two complex avoidance environments are considered. Simulation-1 (*see Figure 39a*) shows that both trajectories reach the goal point. However, the trajectory using the streamfunction (ψ) is much shorter than that using the potential (φ). Simulation-2 (*see Figure 39b*) also indicates that the trajectory using the streamfunction (ψ) has more efficient path than that using the potential (φ).

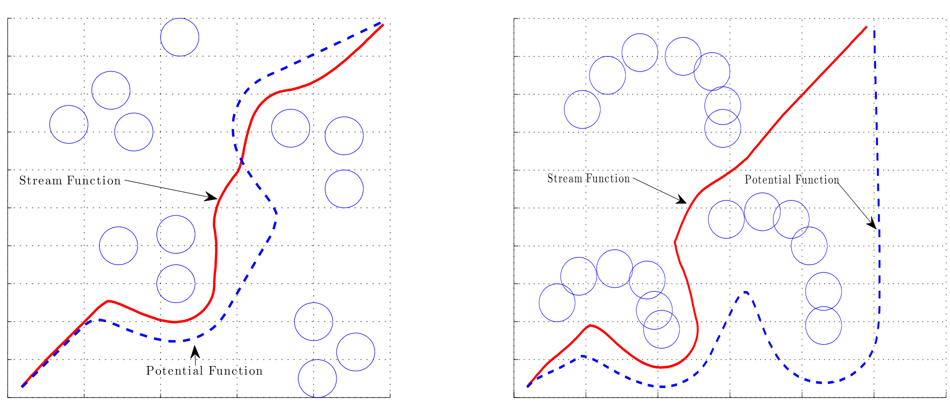
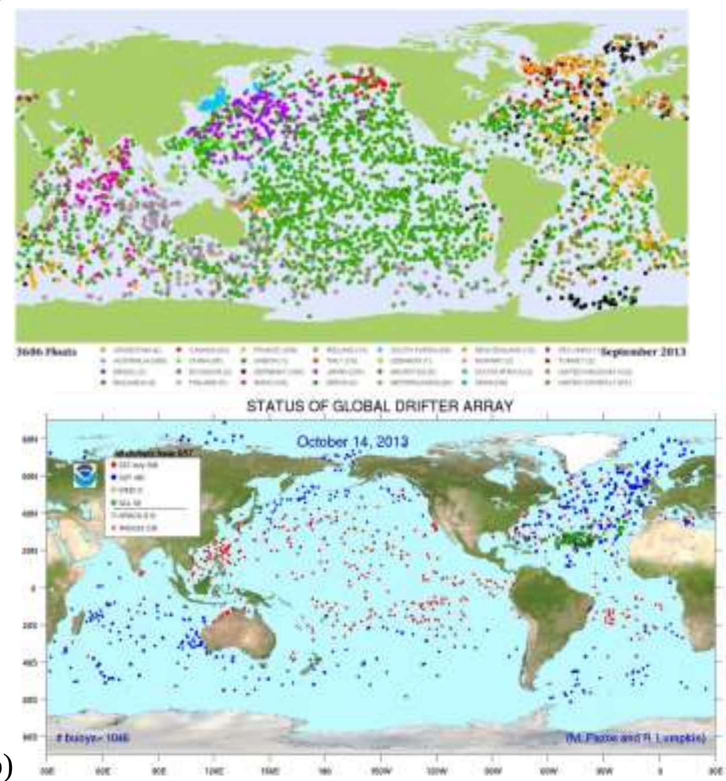


Figure 39. Comparison of avoidance path between stream function and potential methods in analytical flow field: (a) simulation-1, and (b) simulation-2

More than 3600 small (20-30 kg) drifting robotic probes (called Argo profiling floats) have been deployed worldwide. In most cases probes drift at a depth of 1000 m (the so-called parking depth) and, every 10 days, by changing their buoyancy, dive to a depth of 2000 m and then move to the sea-surface, measuring conductivity and temperature profiles as well as pressure. From these, temperature and salinity can be observed (*see Figure 40a*). Satellite-tracked surface drifting buoys observe currents, sea surface temperature, atmospheric pressure, winds and salinity (*see Figure 40b*). Besides, high frequency radars and glider fleets enhance the ocean observational sampling rate and quality.

(a)



(b)

Figure 40. Global ocean observation by (a) drifting robotic probes (Argo profiling floats), and (b) drifting buoys

Effective assimilation of the drifter robotic data into ocean model is challenging. In this project, a new data analysis/assimilation scheme, the OSD, has been recently developed to analyze fields from noisy and sparse oceanographic data. Let (x, z) be horizontal and vertical coordinates and t be time. A physical variable $c(\mathbf{x}, z, t)$ at depth z_k is decomposed using the generalized Fourier series

$$c(\mathbf{x}, z_k, t) = c_0(z_k, t) + \sum_{m=1}^{M} a_m\left(z_k, t\right)\ \Phi_m\left(\mathbf{x}, z_k\right), \quad \mathbf{x} \in R(z_k) \tag{1}$$

where c_0 is the horizontal mean of the variable c. M is the truncated mode number, $\Phi_m(\mathbf{x}, z_k)$ and $a_m(z_k, t)$ are the orthogonal basis functions (or called modes) and the spectral coefficients, respectively; $R\left(z_k\right)$ is the area bounded by the lateral boundary $\Gamma\left(z_k\right)$ at depth z_k. The basis functions { $\Phi_m(\mathbf{x}, z_k)$ } are eigenfunctions of the horizontal Laplace operator ($\nabla_h^2 \equiv \partial^2 / \partial x^2 + \partial^2 / \partial y^2$ **)** with the basin geometry and certain physical boundary conditions. For temperature and salinity, the homogeneous Neumann boundary condition is taken at the solid boundary $\Gamma(z)$ (i.e., no heat and salt fluxes),

$$\nabla_h^2 \Phi_m = -\lambda_m \Phi_m, \qquad \mathbf{n} \bullet \nabla_h \Phi_m |_\Gamma = 0, \quad m = 1, 2, ..., M, \tag{2}$$

where **n** is the unit vector normal to $\Gamma(z)$. The basis functions { Φ_m } are independent of the data and therefore available prior to the data analysis. The OSD method has two important procedures: optimal mode truncation and determination of spectral coefficients {am}. The optimal mode truncation (M) is determined using Vapnik (1982) variational method. Application of the generalized Fourier series expansion (1) to the observational points with P as the total number of observations leads to an algebraic equation

$$\mathbf{Aa} = \mathbf{QY}. \tag{3}$$

where **a** = (a_1, a_2, …, a_M)**,** is the state vector (M-dimensional) ; **A** is a $P \times$ M matrix; **Q** is a $P \times P$ square matrix ($P > M$); **Y** is a P-dimensional observation vector, consisting of a signal $\bar{\mathbf{Y}}$ and a noise **Y'**. Due to high level of noise contained in the observations, the algebraic equation (3) is ill-posed and needs to be solved by a rotation matrix regularization method [2] that provides: (a) stability (robustness) even for data with high noise, and (b) the ability to filter out errors with a-priori unknown statistics.

After the OSD scheme has been developed, three diemnsional ocean velocity vector (u, v, w) is decomposed by

---

[2] See Chu et al. (2004)

$$u = -\frac{\partial \psi}{\partial y} + \frac{\partial^2 \varphi}{\partial x \partial z}, \quad v = \frac{\partial \psi}{\partial x} + \frac{\partial^2 \varphi}{\partial y \partial z}, \tag{4}$$

where ∇^2 is the horizontal Laplacian operator. The ocean currents satisfy the incompressible condition, which leads to

$$\nabla^2 \psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}, \quad \nabla^2 \varphi = -w, \tag{5}$$

where (u, v, w) in the right-hand side of the two Poisson equations are obtained from the real-time ocean current data. The streamfunction (ψ) and potential (φ) are the solutions of the Poisson equations (5). At the obstacle, the stream function $\psi = 0$.

This project shows better performance of using the streamfunction (ψ) method than the potential (φ) method, produces a new ocean data assimilation scheme (i.e., the OSD) to effectively assimilate the observational ocean data (currents, temperature, and salinity, especially by global surface drifter array and Argo drifters), and uses a three dimensional flow decomposition to obtain the streamfunction and potential from the real time ocean observational data. The real-ocean streamfunction will be incorporated into the UUV path planning for various naval operational purposes. Furthermore, our work contributes to the NPS/CRUSER program, ONR surface drifting mine neutralization, and NAVO operational ocean modeling and simulation. The newly developed OSD ocean data assimilation scheme can be used by the two high-resolution NAVO operational ocean models: the Navy Coastal Ocean Model (NCOM) and Delft3D.

Several primary project tasks were completed. 1) The streamfunction method for UUV path planning has been verified using an analytical flow field. 2) The Optimal Spectral Decomposition (OSD) Algorithm for Real Time Ocean Data Assimilation for UUV Path Planning has been completed. 3) The algorithm for calculating the streamfunction from the real-time ocean velocity data has been completed. Navy tactical ocean environmental models and data are very important and useful for the CRUSER program. We will continue our efforts to effectively incorporate the ocean models in the UUV operations. Use of real ocean data (currents, bathymetry, etc.) for the UUV path planning with obstacle avoidance will greatly enhance the Navy's capability in surveillance and detection.

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

d. Countering Adversarial Unmanned Systems: Live-Fly Experimentation with Aerial Combat Swarms

As unmanned system technologies continue to advance, so increases the likelihood of their use by adversaries of the future in capacities such as in swarm attacks. However, current approaches of expending high cost solutions to address these low cost threats is unsustainable in resource-constrained contexts. In these cases, innovation can help defeat inundation. The ambitious grand challenge competition effort described herein presents a novel and unique opportunity to explore advanced tactics for robotic swarms and, more specifically, for defeating these saturation attack scenarios. The Aerial Combat Swarms Swarm vs. Swarm UAV Challenge competition is designed to inspire new concepts of operations and illuminate new tactics in unmanned systems employment, specifically in the swarm and counter-swarm robotics arenas. The competition scenario involves a tournament of live-fly, large scale "battles," where in each such battle two teams comprising many autonomous aerial robots vie for air superiority while simultaneously defending a high value unit on the ground and/or attacking that of the opponent's. The vision for the inaugural grand challenge event is for 50 vs. 50 UAVs by the year 2015. The Aerial Combat Swarms grand challenge competition is envisioned to be staged as a two-week, tournament-style, live-fly outdoor event, where eight qualifying teams engage in a series of single-elimination matches. Points are scored by successful attacks on both the opponent's aircraft as well as its home base, awarded by an arbitrating virtual referee. Each match comprises advance preparation time, a specified launch window during which all battle-ready aircraft must be aloft, two half periods separated by an intermission, and recovery operations at the match's conclusion.

(a) Motivation and Research Plan

Recent reports in the public domain identify the potential use of "saturation attacks," where dozens of kamikaze UAVs execute precision strikes nearly simultaneously, as a serious threat to the U.S.'s military and information superiority. This "swarm" of UAVs, consisting of assets such as the "Harpy" UAV and its derivatives, can loiter autonomously for long durations while seeking radiating targets, thereby rendering vessels employing these systems virtually "blind" to imminent and subsequent threats. In this context, advanced technologies to defeat such threats are of vital interest to U.S. and allied forces around the world.

The above vignette highlights the explosive emergence of unmanned systems in military operations, but increasingly not limited to U.S. and allied employment. The increasing exploitation of low-cost technologies by adversaries has been witnessed in modern day irregular warfare contexts. Coupled with increasing nation-state development efforts in unmanned systems, these threats challenge defense researchers, technologists, and decision makers to study and develop counter unmanned systems tactics, that is, the employment of unmanned systems to defeat those of the adversary. Explicit emphasis on the generation of these tactics will directly enable translation of operational needs to mission specifications to technological requirements.

(b) Competition Design Concept

The scenario provides operational relevance by abstracting a naval context of a surface action group engaging an enemy surface action group (SAG). By construction, the Swarm vs. Swarm UAV Challenge identifies opposing end zones or "flags" as the high value units to be defended/attacked by the respective UAV swarms, as illustrated in the figure below (*see Figure 41*). As an aerial version of the "capture the flag" game, each side seeks to "attack" (i.e., land sufficiently close to) the opponent's flag with its UAV swarm elements, whilst simultaneously "defending" its own flag by intercepting the opponent's inbound UAVs. Further, the time and spatial spans of the scenario are designed to mimic the previously mentioned naval engagement, such that sufficient standoff detection of the adversary is appropriately modeled and scaled.

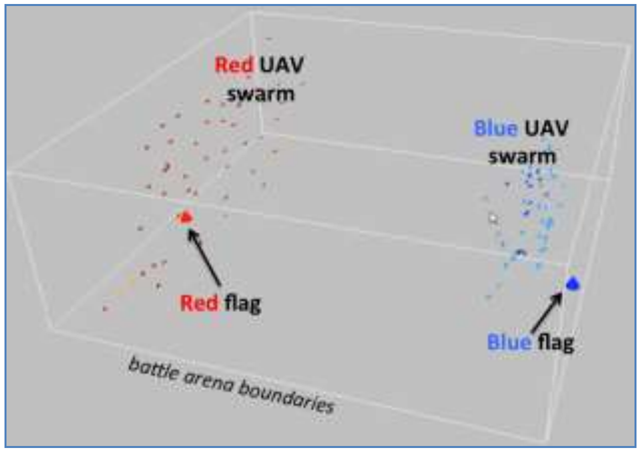


Figure 41. Scenario: Aerial "Capture the Flag" setup with opposing flags and UAV swarms with the battle arena

Ongoing development and demonstration of enabling capabilities at the Naval Postgraduate School have continued to push towards realization of the Swarm vs. Swarm UAV Challenge. Specifically, over the past year, the academic, research, and engineering team in NPS' Advanced Robotic Systems Engineering Laboratory (ARSENL) has made significant and accelerated progress towards fielding an autonomous UAV swarm as a candidate participant in the Swarm vs. Swarm UAV Challenge. We focus the discussion on several key areas and results, highlighting the holistic systems approach spanning swarm concepts through field experiments.

As the rapid pace of technological development in robotic and unmanned systems continues to accelerate, so must the processes and operational constructs also advance in tandem to fully utilize and achieve their potential. In this context, ARSENL engages in an aggressive spiral development approach to rapidly innovate, integrate, and instantiate new concepts and capabilities. The confluence of lower costs for autonomous systems, easier access to experimentation sites, faster identification of issues through crowd-sourced testing, and increasing operational relevance of swarm technologies creates an ideal opportunity for accelerated iterative development. Rather than conventional, more sequential approaches used for development and testing of new technologies, a tight spiral process model often implemented for software development is better suited to ARSENL's needs for "agile innovation" in robotics capabilities. Even a moderately paced, quarterly experimentation schedule (Aug-12, Oct-12, and Jan-13) was too slow to match the pace of development within the ARSENL group. Rather, these experiences led to adoption of a much faster operational tempo of frequent experimentation every four to six weeks (Feb-13, Mar-13, May-13, Jun-13), enabling substantial progress in both refining processes and identifying lessons learned, to be incorporated into subsequent experiment events.

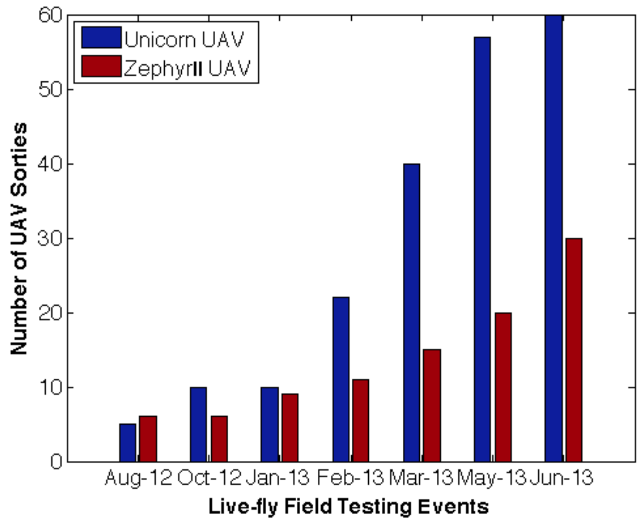


Figure 42. Cumulative number of sorties since start of field experimentation activities

The benefit of this accelerated pace is evident in the figure above (*see Figure 42*) which showcases the number of sorties for two UAV platforms used in live-fly field tests as a function of experimentation event annotated by month. Notably, from the time the ARSENL was established at the Naval Postgraduate School in June 2012 until the team's ability to conduct its first live-fly field experiments in August 2012 (that is, only 2.5 months) readily demonstrates the enabling technologies available through advances in commercial and open-source robotics communities. As a highlight, in the past thirteen months since becoming operational last year, NPS ARSENL has conducted seven experimentation events comprising 90 UAV sorties between two different fixed-wing UAV platforms.

Access to field experimentation sites continues to be a critical enabler for facilitating these rapid advancements in UAV swarm capabilities, such as NPS partnerships with Camp Roberts or Fort Hunter Liggett in California and their restricted airspace and test ranges. The importance of such experimentation locales highlights one of the objectives of the Swarm vs. Swarm UAV Challenge, that is, to *provide a venue* where innovation can be fostered and demonstrated. Though selection of the competition venue has yet to be concluded, the above experiences highlight that such partnerships can be both readily viable and incredibly beneficial to the robotics communities.

(c) Leveraging Both Commercial and Open Source Resources for Swarm UAV Innovation

As evidenced by the rapid explosion of aerial robotics technologies, new capabilities afford new opportunities to innovate, whether in the academic, commercial, or personal domains. Recent efforts at NPS described above highlight the advantages of leveraging commercial-off-the-shelf UAV capabilities as a baseline system on which to gain experience and identify limitations in platform, command and control, and other relevant systems for swarm UAV operations. However, parallel development efforts increasingly focus on leveraging open source resources for flight control, platform, and autonomous capabilities that provide not only significant cost savings but take advantage of an accelerated development timeline due to their crowd-sourced nature.

In order to benchmark current capabilities in multi-UAV research, ARSENL uses its fleet of 60" *Unicorn* UAVs (*see Figure 43*), made by Procerus Technologies (a Lockheed Martin company).[3] These flying wing airframes are manufactured out of EPP foam, are nominally catapult launched, and are powered by lithium polymer batteries with an average endurance of about 45 minutes. Flight speeds can vary with nominal cruise around 20 meters per second (40 knots). Associated with the *Unicorn* UAVs are the *Kestral*™ autopilot for avionics and autonomous flights and *Virtual Cockpit*™ ground control station (GCS) software for real-time flight management. Communication between UAV and the GCS is across 900MHz radio communications, which provides exchange of telemetry and commands.

[3] Lockheed Martin Procerus Techonologies, "Kestrel Flight Systems," http://www.lockheedmartin.com/content/dam/lockheed/data/ms2/documents/procerus/Kestrel_Flight_Systems_2012.pdf, July 2013.

Figure 43. NPS ARSENL fleet of 60" Unicorn UAVs

The COTS ability to fly several UAVs simultaneously through *Virtual Cockpit™* enabled extensive early testing and characterization of such multi-UAV operations, including identification of shortcomings in equipment, operator software, flight preparation processes, and infrastructure. These insights remain invaluable in the design of NPS' swarm UAV capabilities.

To realize these advanced capabilities, the requirements for customizable and modular components, cost effectiveness for large numbers of UAVs, and rapid development and testing are more so critically important, and as such, we look to leverage open-source resources and low-cost solutions to commercial alternatives. Examples of such resources include open-source hardware and software designs for flight control, autonomy, and management, like the APM or PX4 autopilots, community-developed APM:Plane firmware, and *Mission Planner* or *QGroundControl* ground control station software.[4,5] Coupled with a rapidly increasing hobby and consumer marketplace for (semi-) autonomous small UAVs (e.g., RC/model aircraft), the open-source community offers substantial benefits in virtually all elements of the systems development process.

4 Swiss Federal Institute of Technology, "PX4 Autopilot." https://pixhawk.ethz.ch/px4/modules/px4fmu .

5 DIYDrones.com, "APM:Plane." http://plane.ardupilot.com/

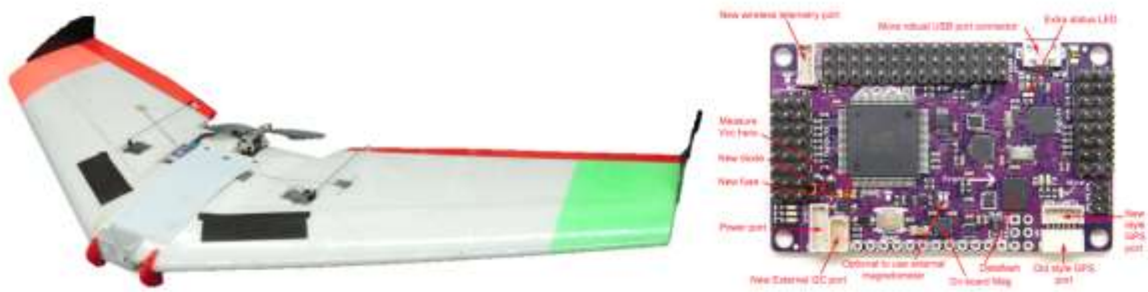


Figure 44. Prototype NPS ARSENL UAV designs integrating low-cost Ritewing ZephyrII RC aircraft platform (left) and the open-source APM autopilot (right)[6]

As a prototype and baseline system, the NPS ARSENL team constructed several initial iterations using the Ritewing *ZephyrII*[7] flying wing, which is nominally an RC model aircraft, and integrated the open-source APM autopilot, as illustrated in the figure above (*see Figure 44*). The *ZephyrII* has a 56” wingspan (770 sq. inches wing area), with elevons and throttle as its control inputs in the flying wing configuration. The APM autopilot provides a variety of interfaces, including outputs for motor, servos, and additional telemetry as well as inputs from sensors, e.g., GPS, barometer, airspeed, magnetometer, inertial measurements, and also command messages from the ground control station.

As the number of planes per mission increases, the efficiency of the flight line becomes more and more important. Since planes have a limited endurance, takeoffs and landings need to take place as quickly as possible.

One of the means we used to speed up preflight checks was to parallelize tasks. Initially we had a single preflight checklist, but we found that some things could be done at the same time. While the flight technician is checking the plane for physical defects, the GCS operator checks to ensure that the radios are functional, that software settings are correct, etc. During final preparations before launch, flight techs can perform the motor run-up check and prep the plane on the launcher while the GCS operator confirms waypoint placement, geofence placement, GPS connectivity, and obtains permission to takeoff from the tower.

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6 DIYDrones.com, “APM:Plane.” http://plane.ardupilot.com/

7 Ritewing RC, “ZephyrII RC Aircraft.” http://www.ritewingrc.com/ .

Another means to decrease preflight check time was to identify tasks that only need to be performed once per day or once per trip and remove them from the checklist used for every flight. Radio channel settings and center of gravity are verified before the first flight of an entire event and do not need to be checked again until the next event unless the plane suffers a hard landing. Emergency beacon tests and range checks only need be performed at the start of every day of an event.

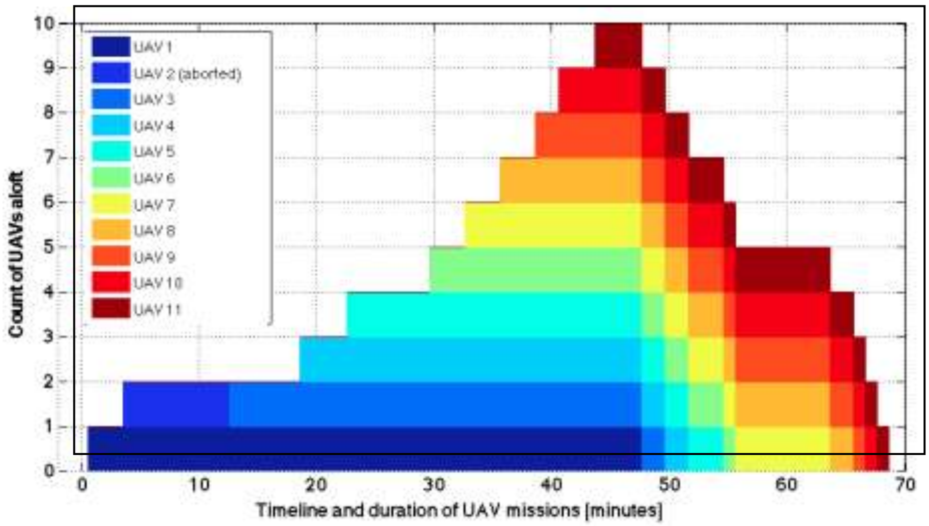

Figure 45. Ten-UAV Mission Timeline, including time between launches and recovery

The resulting capabilities afforded by these enhancements to flightline operations include the successful deployment and operation of ten UAVs during recent field experiments. The objectives of these experiments included demonstration of the impact of improved logistics processes and determination of the workload levels for flight technicians and ground operators (rather than on cooperative multi-UAV behaviors). The timeline and visualization of the launch, flight, and recovery of the UAV fleet are illustrated in the surrounding figures (*see Figures 45 and 46*). One can observe the challenges faced when attempting to deploy larger numbers of UAVs, including the required time for a launch window for current approaches using a manual catapult launching system. Further research in automated and/or parallel launch capabilities is clearly merited to address this challenge.

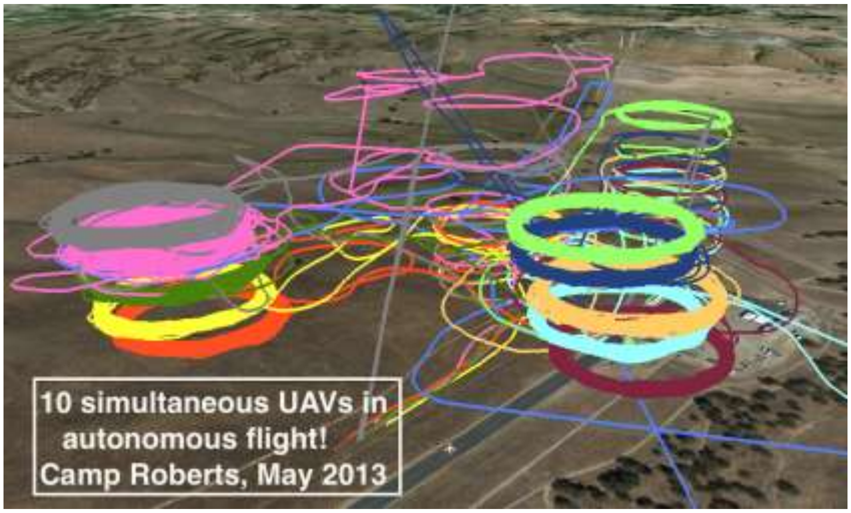

Figure 46. Trajectories of the Ten-UAV Mission (Camp Roberts, Calif., May 2013)

(d) Algorithms for UAV Swarm

Studies have been done on the coordination of teams of UAVs sharing a common goal, but typically team sizes are small, numbering from two to ten.[8,9,10]. Other relevant studies do employ larger swarms, but their models are based on cellular automata and individual agents in a swarm are not as complex as an individual unmanned aerial systems (UAS).[11,12,13]

The breadth of the research challenges posed by exploring and developing swarm UAVs, ranging from advances in swarm tactics to integration efforts for swarm live-fly operations, ensures that many opportunities for innovation, largely through conversation and collaboration, are readily available. The Swarm vs. Swarm UAV Challenge presented in this paper, as well as the preliminary research efforts at the Naval Postgraduate School in swarm UAV concepts and capabilities, demonstrate the rapidly changing landscape of future robotics and unmanned systems, particularly in collective systems of large numbers of autonomous agents, whether cooperative or adversarial. It is

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8 See Bellingham et al. (2003)

9 See Jin et al. (2003)

10 See Shetty et al. (2008)

11 See Fukuda et al. (1989)

12 See Guo et al. (2011)

13 See Prencipe and Santoro (2006)

the intent of this outlined effort to inspire innovation in key research areas that have the potential to initiate longstanding impact across academic, defense, and commercial robotics communities.

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e. A Collaborative Diver Assistant for Underwater Operations

For the last two decades, robotics research has focused on individual capabilities, such as traveling between points and obstacle avoidance. However, a fundamental shift is occurring: robots are increasingly being put to work in real-world environments. These environments tend to be complex and cluttered, and the tasks are complicated, requiring advances in controls, sensing, perception, and communication. This research focuses on a robotic underwater co-worker for activities that involve human divers.

Diver operations are inherently dangerous. Physiological effects limit dive duration and frequency and necessitate a large support crew, increasing operational costs. The sensory-deprived underwater environment makes navigation, communication, and documentation challenging. The Center for Autonomous Vehicle Research (CAVR) has a robotic diver assistant system to provide autonomous support to diver teams, which has the potential to significantly enhance underwater operations. The project is aimed at providing utility to the diver team (e.g., illumination, improved situational awareness, etc.) without burdening the team with vehicle command and control, thereby augmenting the diver team and allowing more effective, efficient, and safer operations. This research program seeks to go beyond co-inhabitance of man and machine—our aim is to fundamentally enable the transformative capability of robots as underwater co-workers.

Unlike traditional Autonomous Underwater Vehicle (AUV) applications, the robotic diver assistant requires high-resolution sensing and communication over short ranges and full motion (longitudinal, lateral, and vertical). This departure allows for the application of different sensing and communication technologies and pushes the operational envelope for AUV systems. This research aimed at establishing a baseline capability to allow CAVR researchers to develop and test advanced autonomy algorithms and capabilities for and from other domains (e.g., UAVs) and combined human-robot operations in a safe environment. The slower environment- and platform dynamics allow more decision time and thus complicated autonomy strategies (that require more decision time) can be evaluated. The technology is relevant to several Naval communities, including Undersea Warfare, Naval Special Warfare, Explosive Ordinance Disposal and Salvage Diving. Another related application area is space exploration. The NASA Analog Studies program which focuses on terrestrial analog environments for space operations, tests and evaluates technologies and procedures for space such as extra-vehicular activities (i.e., space walks) (*see Figure 47*). Finally, the diver-assist technology has also been proposed for scientific diver support (e.g., underwater archaeology and marine biology). Thus, the proposed technology is not only provides a development platform and test bed for continued autonomy research, but is inherently relevant to the space, underwater, and military communities.

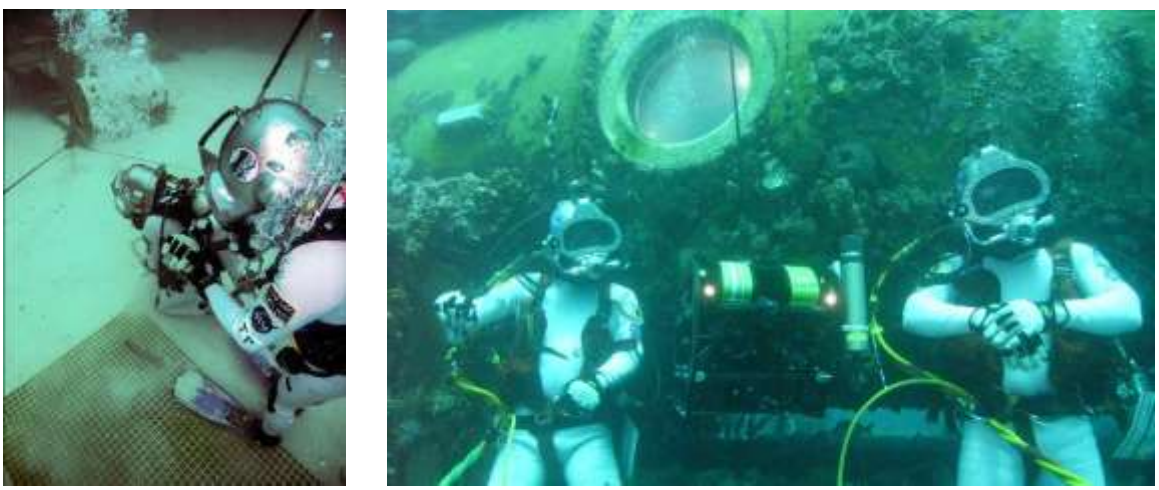

Figure 47. NASA Aquanauts (left) performing tasks in simulated Space Walks[14], which bears a close resemblance to underwater EOD tasks, etc. The Aquanauts with the NPS CAVR Tethered Hovering Autonomous Underwater System (THAUS) at the Aquarius Habitat in Key Largo, FL.

Consider a robot-diver team that has to perform ship hull inspections at sea. Outside of the protected harbor environment, the currents, surge, and ship motion impact diver operations. Varying visibility conditions necessitate the use of acoustic

[14] http://www.nasa.gov/exploration/analogs/

imaging for inspections and to build survey maps. The robotic diver assistant can interactively build these maps in real time, which can be used by the divers and/or robot to navigate to the desired location. From the surveys, irregularities on the hull can be identified (by the diver, command, or robot). The robot transports a diver toolset to the objective. Once on location, the robot provides utility to the diver by illuminating the workspace or providing an alternative view of the objective via video feed (to either the diver or the command). Once the task is completed, the robot can lead the diver back to the diver platform for extraction. The robot can also provide emergency communications or navigation assistance. The robot operates in the same space as the divers, but the diver team is not burdened or constrained by the robot.

(a) Technical Approach

To realize the overall objective of a robotic diver assistant, research in the following domains is required:

- Develop autonomy and decision strategies for mixed human and unmanned systems operations.
- Enhance existing underwater survey capabilities for high-resolution local survey maps and interactive (semantically augmented) map building.
- Investigate safe robot operations among moving divers while accounting for currents, and navigation using the generated map.
- Investigate closed-quarters robot navigation with static divers and environment features (e.g., reefs, structures, etc.) while accounting for surge and currents.
- Develop diver-robot communication schemes and robot-diver information transfer and display capabilities.

For this research, the following specified tasks were identified to establish a baseline autonomous capability suitable for continued research and that can be leveraged to pursue additional external funding. The combination of these tasks will provide basic operation among the human divers and a station-keeping capability.

Figure 48. The SeaBotix vLBV300 ROV platform

The envisioned robotic diver assistant will be a fully autonomous, untethered platform such as the SeaBotix vLBV300 Remotely Operated Vehicle (ROV) (*see Figure 48*). To facilitate safe operation among human divers and close to the ocean bottom, the platform must have omnidirectional control authority in the horizontal plane, as well as vertical and yaw control. These control requirements differ substantially from traditional AUV platforms, which are designed to travel very efficiently in the forward direction, with very limited lateral control. No commercially available AUV has been identified with the required degrees of freedom and that is small enough to allow safe operation with human divers. However, the SeaBotix vLBV300 ROV[15] satisfies the above requirements and NPS USW is funding the acquisition of this platform. The platform is designed for remote (tethered) operation via a surface control station and allows longitudinal, lateral, and vertical motion for the system to overcome surge and currents and operate safely with human divers. SeaBotix made the digital control interface used by the ground control station available, and CAVR researchers implemented a high- and low-level control interface with the platform. This resulted in the tethered hovering autonomous underwater system (THAUS). The control interface is built on the robot operating system (ROS). Furthermore, the system has been augmented with a Greensea System INS system that provides additional control interfaces.

[15] http://www.seabotix.com/products/vlbv300.htm

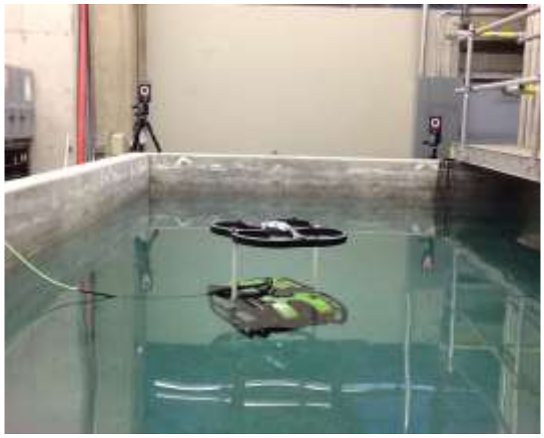

Figure 49. THAUS in the CAVR test tank with the VICON motion capture system

LT Josh Weiss developed a hydrodynamic model, which captures the motion and response of the platform to control inputs, as his Master's Thesis research presented at IEEE Oceans 2013. [16] The approach is based on online System Identification techniques and relied on externally obtained vehicle localization data. For example, the VICON Motion Capture system[17] to learn the dynamic response of the system. Experimental results from the CAVR test tank (*see Figure 49*) allowed for the generation of a 3-DOF dynamic model in Surge, Sway, and Yaw. Physical considerations prevented model identification in the Heave, Roll, and Pitch channels. Theoretical results were obtained for these channels. Combined with the newly integrated INS, ocean tests are being planned to obtain the full 6-DOF model. The obtained model was additionally utilized to implement a system simulator.

The robot diver assistant must share the operating environment with human divers: the robot must navigate relative to the environment to reach a specified site location (along with moving divers), then maneuver among the mostly static divers as they perform their tasks on location. One feature of the underwater diver assistant application that can be leveraged is the slower environment dynamics: the divers' and robot's mobility is inherently limited. These dynamic characteristics make this application domain attractive for the development of complex navigation algorithms since the decision cycle can be extended. On the other hand, accurate measurements of

[16] See Weiss and DuToit (2013)

[17] http://www.vicon.com

the underwater environment are difficult to obtain and large environmental disturbances exist. The robot has to operate in close proximity to the sea bottom (reefs, rocks, over-hangs, etc.) and the divers and as a result it is critical to anticipate and account for the disturbances and uncertainties in the environment when solving the planning problem to ensure diver and robot safety.

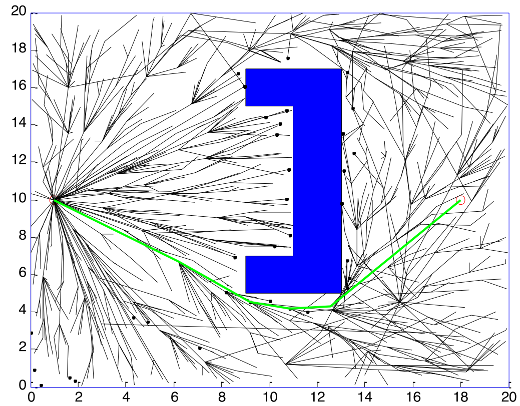

Figure 50. Site-relative navigation and diver leading requires deliberative plans that avoid obstacles and account for diver motion.

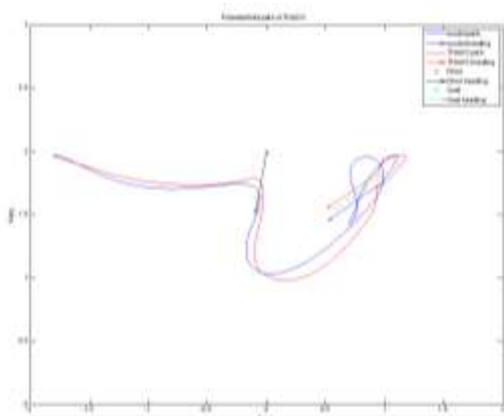

Figure 51. Diver-relative navigation, based on Artificial Potential Fields, obtained in simulation and the CAVR test tank

Three initial navigation capabilities have been identified to enable a basic diver assist capability and are the focus of the current proposal: station keeping, navigation to a specified location in the operating space, and diver-relative navigation. Station keeping requires feature-based navigation (as provided by the SLAM framework). Site-relative navigation requires a combination of feature-based navigation and terrain-relative navigation.[18] LT Andrew Streenan investigated this problem as his Master's Thesis research. Diver-relative navigation based on Artificial Potential Fields,[19] and site-relative navigation with diver leading based on a deliberative planning approach that leverages the RRT* algorithm[20] and obstacle avoidance while accounting for diver motion are illustrated in his work (*see Figures 50 and 51*). Since the vehicle has independent control in the surge, sway, and yaw directions, the surge direction is used to match diver velocity, the sway is used to minimize cross-track error, and the yaw channel is used to point the vehicle towards the immediate objective. These results were presented at IEEE Oceans 2013 conference.[21]

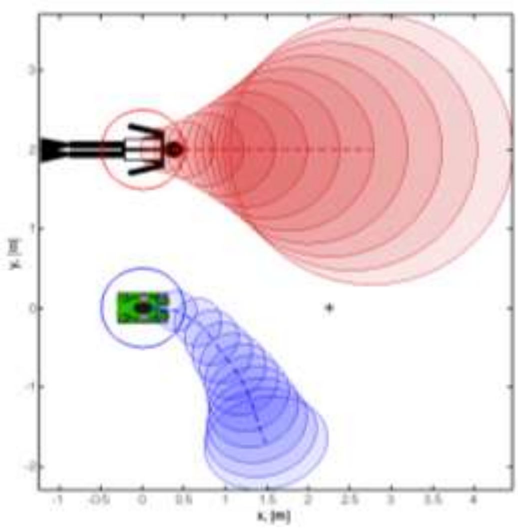

Figure 52. Uncertainty growth causes conservatism and an inability to perform tasks.

Finally, an approach was investigated that additionally takes into account the quality of the information about the environment and vehicle or diver positions. This approach, based on the Partially Closed-Loop Receding Horizon Control approach,[22] is computationally intensive, but accounts for the knowledge (or lack thereof) when planning motion around divers, and also uses a simple behavioral model to capture the uncertainty associated with human motion. When anticipated information is ignored, the

[18] See Meduna et al (2008)

[19] See Choset (2005)

[20] See Karaman and Frazzoli (2011)

[21] See Streenan and DuToit (2013)

[22] Du Toit, N.E.; Burdick, J.W. (2012)

solution space is limited due to the growth in uncertainty and the solutions tend to be very conservative. This limitation can be overcome by accounting for anticipated measurements and information (i.e., partially closed-loop), allowing for a drastic reduction in uncertainty growth (*see Figures 52 and 53*).

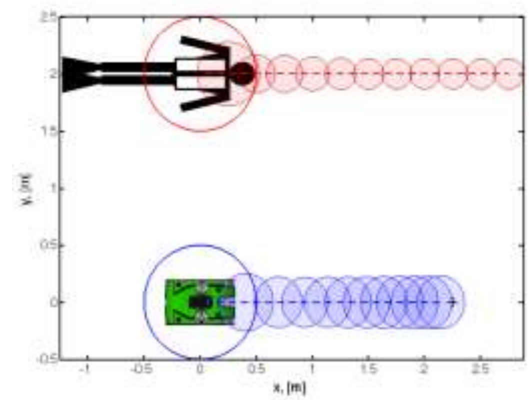

Figure 53. By accounting for anticipated information, efficient solutions can be obtained while maintaining vehicle and diver safety.

(b) Field Experimentation

Thesis students included in this research effort included LT Andrew Streenan (USW) and LT Josh Weiss (USW). CAVR also established a collaborative partnership with NASA Johnson Space Center and participated in the NASA Analog Studies SEATEST II field experiment in September 2013 (*see Figure 54*). The experiment spanned two weeks and took place at the Florida International University (FIU) Aquarius Reef Base[23] in Key Largo, Florida. NPS deployed 2 REMUS 100 AUVs and THAUS to perform wide-area surveys (REMUS), share information between dissimilar vehicles (REMUS and THAUS), and provide basic diver support with THAUS. This initial collaboration was partially supported by CRUSER. CAVR researchers are processing the data, which will be presented in the near future.

[23] http://aquarius.fiu.edu/

Figure 54. NASA Aquanauts with the NPS REMUS 100 and THAUS in front of the Aquarius Reef Base.

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f. The Use of Unmanned Systems for Environmental Sampling and Enhance Battlespace Awareness in Support of Naval Operations)

The general objective of this research was to improve the ability of the U.S. Navy to use unmanned systems for collection of environmental data. This effort addressed the use of unmanned aerial systems (UAS) for collection of atmospheric information. The main focus was on atmospheric features which affect the propagation of radio frequency (RF) transmissions.

This effort developed and analyzed methods to exploit the use of meteorological data obtained from UAS platforms for enhanced battlespace awareness in support of naval operations. Weather conditions can have major impacts on naval operations, and in some cases, correctly predicting the effects of these conditions can make the difference between mission success or failure. High winds, dust, precipitation, and extreme heat and cold can have major impacts on naval operations, but the main focus for this FY2013 effort was on the atmospheric impacts on RF systems, such as radar, communications, jamming, surveillance and weapons systems.

There were two aspects to this research: (1) performing key measurements in the Trident Warrior 2013 field program and (2) testing the use of the InstantEye UAS as a platform for meteorological measurements. After some background information this report will describe the efforts and results for each of the above aspects, followed by conclusions and planned recommendations for future research.

Usually the most significant environmental effects on propagation of RF waves are caused by changes in the index of refraction of the atmosphere. These changes cause refraction, or bending of RF waves, which can result in large changes in propagation ranges and performance of systems that use long range RF radiation. We quantify the index of refraction by use of a parameter called the Modified Refractivity or "M". M depends on the pressure, temperature and humidity of the atmosphere; changes in the vertical gradient of humidity are particularly important. In situations where moist air is below dry air, ducting can occur, which means that the RF rays are bent downward more than the Earth's curvature, causing greatly extended propagation ranges. To predict the performance of systems using long range (> 10 km) RF transmissions, vertical profiles of M are input into tactical decision aids such as the Advanced Refraction Effects System (AREPS).

Until about 10 years ago, the primary method used by the U.S. fleet to determine M profiles was to launch weather balloons with devices called radiosondes which have pressure, temperature and humidity sensors. Most battle groups had at least one vessel that was capable of performing these measurements. These measurements provided both real time "nowcasts" of refractive conditions and also were used as input into numerical weather models which produced forecasts of future weather conditions and refractive features. Radiosondes are still launched twice a day at hundreds of stations around the earth and are the most important tool for characterizing the details of atmospheric structure in use today. However for various reasons, radiosonde measurements have been virtually eliminated in all U.S. Navy operations (although they are still used by other countries' navies). More emphasis is now placed on numerical weather model forecasts and nowcasts to determine M profiles and hence as input into tactical decision aid predictions of RF systems performance. However, without radiosonde data to describe local conditions and as input into weather prediction models, the U.S. Navy's ability to predict RF system performance has been significantly degraded.

(a) Trident Warrior 2013

Trident Warrior 2013 was a Navy operation which occurred off the coast of Virginia 13-18 July 2013. During TW13, the PI and colleagues used the research vessel R/V Knorr as a platform for testing the capabilities and usefulness of UAVs for collection of atmospheric and oceanographic environmental information with emphasis on descriptions of current and future RF propagation conditions. The main question being addressed (as quoted from the ONR sponsor) was

> *"Do on scene meteorological and oceanographic observations from UAVs provide increased, tactically significant skill for EM propagation prediction over a model-only solution from COAMPS[24]/AREPS, as compared to the Navy's cancelled radiosonde program?"*

Researchers from several groups performed a variety of meteorological, oceanographic and RF measurements in support of the objective. Scan Eagle UAVs with meteorological sensor payloads were flown from the R/V Knorr for a total of 48 hours flight time. The meteorological data were transmitted back to the ship and from there sent to the Naval Research Laboratory (NRL) in Monterey CA. At NRL, the Scan Eagle data were included as inputs (along with a variety of other data sources) to initialize COAMPS model runs, which in turn produced predicted profiles of M and other atmospheric parameters. In addition, COAMPS was run with the Scan Eagle data withheld. This allowed the COAMPS predictions with and without the Scan Eagle data to be compared, thus quantifying the impact of including the additional UAV input data on the forecasts, particularly the M profiles and resulting RF system performance. This was all done in the context of a variety of other measurements which allowed detailed characterization of the physical and RF environments.

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[24] COAMPS is the U.S. Navy's mesoscale numerical forecast model

NPS, with funding from CRUSER, played a key role in the TW13 atmospheric measurement program. The author used free balloon radiosondes to sample the entire troposphere and provided a reality check for the COAMPS predications and also to quality check the Scan Eagle measurements. On each day in the 13 -17 July time period, the author also performed low level, high resolution atmospheric measurements using kites and tethered balloons as platforms (*see Figure 55*). Due to lack of NAVAIR flight clearance, the author was not able to perform atmospheric measurement flights with a mini quad rotor UAV. However, the kite and tethered balloon platforms served as close proxies for miniature UAV measurements.

Figure 55. Tethersonde operations from a small boat during TW13. A radiosonde (not visible) is attached below the balloon which is raised and lowered several times from 1 m to 200 m elevation. These measurements were a proxy for mini quad rotor UAV sampling of the atmosphere.

The author also helped deploy buoys with meteorological sensors developed at the Naval Postgraduate School by Mr. Dick Lind. These deployments were funded outside of CRUSER as part of a program led by Dr. Qing Wang of the NPS Meteorology Department.

In addition to the measurements described above, other groups performed “up/down” radiosonde soundings, signal strength measurements from various shore and ship based RF emitters (radars and radios). Oceanographic measurements included Wavegliders with met and ocean sensors, drifting wave buoys. SLOCUM and Seaglider UUVs and dropped AXBTs (underwater sensors) from manned aircraft P-3 flights.

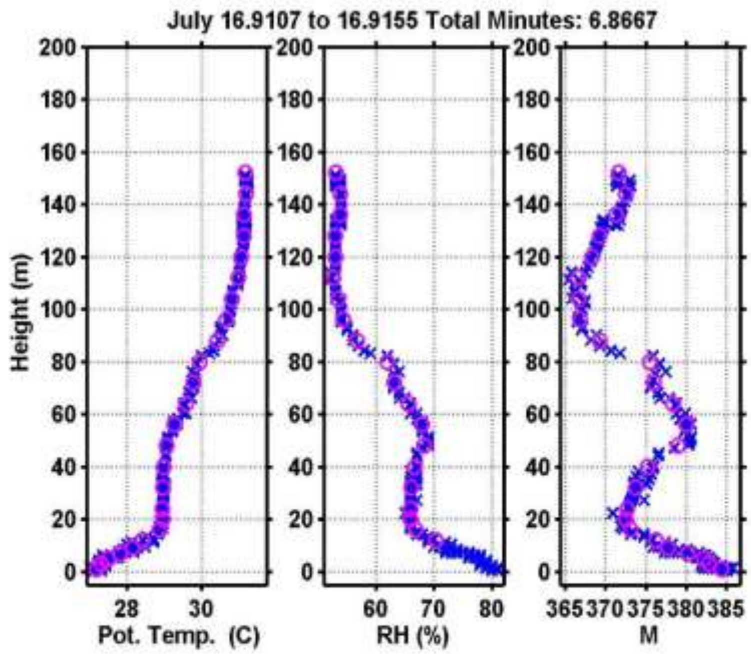

Figure 56. Tethered balloon (UAV proxy) profiles of Potential Temperature , Relative Humidity (RH) and Modified Refractivity (M) on 16 July, 2013 during TW13. Note the complicated low level structures in M. These structures cannot be resolved by numerical models

TW13 demonstrated that meteorological and oceanographic (METOC) measurements from unmanned systems can be integrated into U.S. Navy operational forecast systems and result in improved predictions of atmospheric structure, including RF propagation conditions in most cases. Initial results show that inclusion of additional METOC data is most valuable for nowcasts and short term (< 6 hour) forecasts. Atmospheric conditions were more complicated than expected, which provided a variety of test cases. Various atmospheric RF ducting features were present during the cruise period and often occurred at multiple levels, which is not typical for that location and time of year (*see Figure 56*). The COAMPS numerical weather forecasts were challenged by the complex conditions and missed many of the refractive features that were present. This inability to accurately quantify refractive conditions in coastal regions is a common problem with all numerical weather models.

Trident Warrior 2013 demonstrated that, in many situations, in situ measurements are required to accurately quantify refractive conditions. Now that the Navy has eliminated radiosonde soundings, can UAVs fill in this need? Scan Eagle represents a mature sophisticated technology and the Trident Warrior 2013 results showed that it can provide accurate humidity and temperature profiles not only at a mother ship location but also in the surrounding region. However because it is risky to fly Scan Eagle very low to the surface (< 30 m), it cannot sample low enough to resolve some types of refraction features such as evaporation ducts and shallow surface ducts. Free balloon radiosondes measurements also cannot resolve these low level features due to their launch height from ships and inadequate resolution.

The author’s kite and tethersonde measurements demonstrated the importance of these low level features in controlling RF propagation over the ocean (*see Figure 57*). However these measurements would likely be impractical for use during Navy military operations. The author believes a viable alternative for obtaining crucial information in the lowest 200 meters of the atmosphere (and especially the lowest 30 m) would be the use of mini quad rotor UAVs as atmospheric measurement platforms.

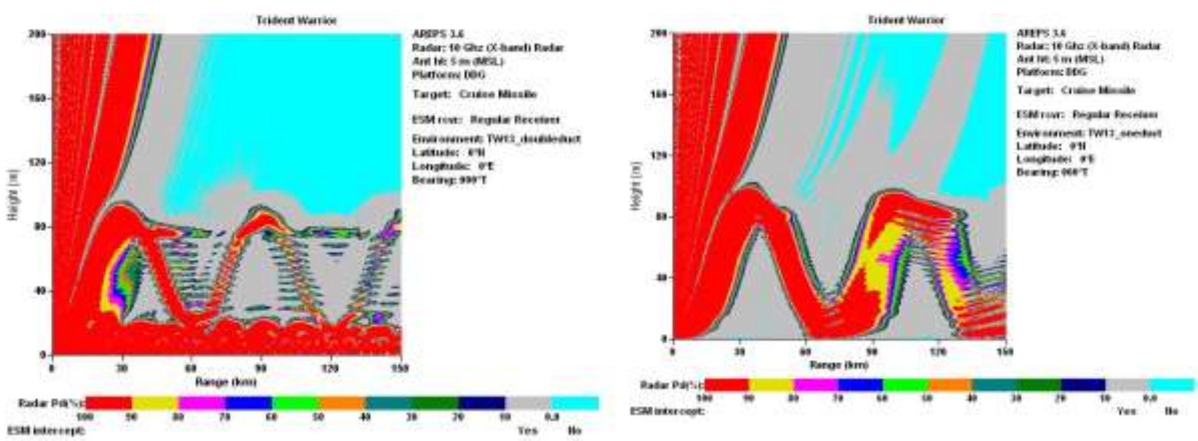

Figure 57. AREPS predictions of coverage for X band radar based on the tethersonde data shown in Figure 2 (*left*). Vertical axis is height and horizontal axis is range. Red indicates 100% predicted probability of detection. The right side shows the same predict

(b) Mini Quad Rotor UAVs

The second main aspect of the PIs FY2013 CRUSER funded efforts involved the testing of various UAVs as platforms for meteorological measurements. Most UAVs have the capability of performing these measurements; the Scan Eagle operations during Trident Warrior 2013 are one example. During TNT and JIFX field programs the author has tested this concept on various UAV platforms using radiosonde sensors, including small delta wing types (not shown). Another tested platform was the InstantEye mini quad rotor UAV manufactured by Physical Sciences, Incorporated. The InstantEye uses GPS and inertial navigation to simplify flight operations. The InstantEye is battery powered and can be safely flown with minimal pilot training.

The author performed several tests (with PSI pilots) at McMillan field, Camp Roberts using the InstantEye UAV with radiosonde sensors attached (*see Figure 58*). The results show that InstantEye is capable of performing accurate low level measurements of pressure, temperature and humidity. The air motion created by the propellers helps ventilate the temperature and humidity sensors, which is needed to prevent solar and infrared radiation contamination. In the lowest two meters above the surface, the downwash interacts with the ground and the mixing of this low level air layer creates some errors if strong temperature or humidity gradients are present. These effects need to be quantified more precisely.

Figure 58. InstantEye UAV with Vaisala RS-92 radiosonde attached on bottom. The UAV is hovering next to a temperature/humidtiy sensor (left side) to verify and validate the UAV/radiosonde measurements

(c) Conclusions and Future Research

There is a need in the U.S. Navy for more accurate characterizations of the RF environment than can be provided by numerical weather forecasts based on routine environmental inputs. The TW13 results (*see Figure 59*) showed that including *in situ* data from UAVs usually results in improved forecasts, but it is not clear if this improvement is worth the cost and logistical needs required. A problem is that, for various reasons, the numerical forecasts have difficulty accurately specifying refractive conditions, even with UAV data used as inputs, particularly in complicated situations that often exist near coastlines and for very low level features. In the context of naval operations, the most valuable use of UAVs for atmospheric measurements appears to be in providing detailed information on current conditions rather than as input into numerical model predictions of future conditions. This means that an ideal UAV for use when there is a need to quantify refractive conditions should be rapidly deployable and easy to operate. Mini multi-rotor UAVs (InstantEye is one example) appear to be able to fill this role for characterizing low level RF refractive conditions.

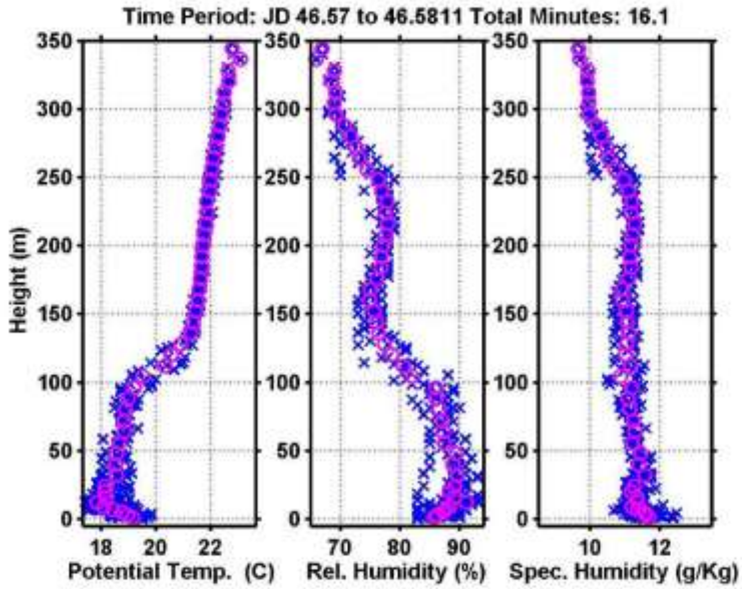

Figure 59. Atmospheric data obtained from a radiosonde attached to the InstantEye UAV at McMillan Field, Camp Roberts, CA. Blue crosses are instantaneous measurements and purple circles are height bin average values. These are data from several soundings and show variability due to turbulence. Note the decrease in temperature (right) and specific humidity (left) with height near the surface, features that are difficult to sample with most types of UAVs.

The author has funding to continue research into using UAVs as atmospheric measurement platforms in FY14. Analysis of the rich TW13 data set will continue in collaboration with the other involved researchers. The author is seeking NAVAIR flight clearance and permission to use lithium batteries so that he can personally test InstantEye for atmospheric measurement use. This testing will include detailed verifications at Camp Roberts and quantification of ground effects. This will be performed by flying the UAV next to towers instrumented with meteorological sensors. Also planned are tests from small vessels off the California coast. A major challenge will be convincing the Navy operational community of the value of these types of measurements. To address this challenge, more complete validation and verification tests will be performed. The PI will seek student involvement in these efforts.

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

g. Comparative Analysis of X-47 UCAS and F-18 Squadron Manpower

This research takes the opportunity to address the challenges of integrating Unmanned Carrier Launched Airborne Surveillance and Strike (UCLASS) aircraft with a carrier-based air wing. The interaction of UCLASS aircraft with traditional air wing asset management planning and flight deck cycles calls for a systematic analysis of the issues of integration. The issues will address manpower as it relates to maintenance, watch standing, and emerging cultural changes in Naval aviation as part of carrier based flight operations and related mission effectiveness. This research will be conducted by examining DoD, various service specific policy and lessons learned, accepted manpower policy as its basis for future manpower estimates.

In response to Warfighter demand, the Department of Defense has continued to invest aggressively in developing unmanned systems and technologies. That investment has seen unmanned systems transformed from being primarily remote-operated, single-mission platforms into increasingly autonomous, multi-mission systems. The fielding of increasingly sophisticated reconnaissance, targeting, and weapons delivery technology has not only allowed unmanned systems to participate in shortening the "sensor to shooter" kill chain, but it has also allowed them to complete the chain by delivering precision weapons on target. The Unmanned Systems Roadmap addresses the benefit of these systems and technologies into the resultant combat capability by mapping specific unmanned systems to their contributions to Joint Capability Areas (JCAs) such as Battlespace Awareness, Force Application, Force Support, and Logistics. [25]UCLASS are expected to provide global intelligence, surveillance, reconnaissance and strike capability. The strategy also reflects efforts to increase global range, persistence, and network connectivity to the carrier. The research will highlight the following features-carrier based, operation and maintenance regarding unmanned operations. Integration of UCLASS with a carrier-based air wing also brings challenges and issues that will be analyzed.

This research approach was to develop UCLASS manpower. It analyzed the current methods being used to provide UAV and related systems manpower requirements were conducted, then a comparative analysis was completed of an existing F-18 and other squadron manpower documents (SQMD) as a baseline to develop alternative UCLASS notional squadron(s). The results will be used to develop current

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[25] DoD FY2009-2034 Unmanned Systems Integrated Roadmap, March 2009 http://www.acq.osd.mil/psa/docs/UMSIntegratedRoadmap2009.pdf

and future UAV manpower estimates. The research included NPS manpower researchers and a Manpower Systems Analysis (MSA) 847 curriculum student thesis.

POC: Dr. William Hatch (wdhatch@nps.edu)

h. Tactical Long Endurance Unmanned Air System (TaLEUAS)

U.S. armed forces increasingly rely on missions by small special operation teams in remote areas. These operations typically require strong networking and ISR support. Currently the required support is provided either by manned aircraft or mid and large scale UAVs such as Predator and Global Hawk. Deployment of these assets requires large teams of ground personnel and has to be planned with significant lead time, and due to the cost of operations, these assets are not available for every mission.

Additionally, the ability to stay aloft for extended periods of time is generally reserved for larger, non-tactical systems. Smaller UAVs (man portable) typically are limited to an hour or two of endurance, must be packed in by the SOF operators, and have limited functionality. If the endurance capabilities of larger UAVs were also achieved by much smaller systems, then smaller (cheaper) UAVs would be able to carry out many missions limited to larger, long endurance systems today.

Even the larger assets like Global Hawk and Predator burn fossil fuels, and their endurance is limited by the size of their gas tank. To achieve 24/7 coverage currently requires several of these assets that take turns on station. The only way to overcome this constraint is by absorbing the necessary energy needed to sustain flight and power the avionics and payloads from the environment.

The concept proposed in this study is designed to harvest energy in two forms from the environment, both photovoltaic and thermal, and combine this with intelligent flight controls that optimize absorption and storage of energy in order to extend flights to days, weeks or months. Additionally, by using a flock of these small gliders, operating cooperatively, the chances of success for the entire team are improved, and 24/7 coverage over the area of interest can be guaranteed.

NPS faculty personnel include Associate Professor Kevin Jones, Associate Professor Vladimir Dobrokhodov, and Professor Isaac Kaminer. Student participants in this research include LT Nahum Camacho (MX Navy), M.Sc. (NPS MAE) and Kevin-Paxti Le Bras (UCSC).

(a) FY13 Progress and Results

Research efforts in FY13 were focused in several areas: electrical system design, integration of the photovoltaic cells in the airframe, performance characterization of the existing airframe, and optimization of the soaring and cooperative control algorithms. Accomplishments in several areas are summarized here.

Coming into this project, Tactical Long Endurance Unmanned Air System (TaLEUAS) utilized independent Lithium Polymer (LiPo) battery packs to provide power for avionics and propulsion. These packs were charged on the ground prior to flight, and the aircraft was required to land if either pack dropped to a prescribed low-voltage threshold. This set a flight-time limit, based on either the avionics pack after about 3 hours, or possibly sooner if lift was difficult to locate on a particular day and the propulsion pack was depleted quickly. Efforts this year focused on transitioning to an onboard solar recharge capability, which would extend flight time to daylight hours. Some details of the transition are described on the following subsections.

A primary goal this year was to integrate a solar array and accompanying electrical system to allow for inflight charging of batteries, allowing for dawn-to-dusk flights. Early efforts went into locating suitable photovoltaic cells and a process to integrate them into the airframe in such a way that they would not adversely affect the aerodynamic performance of the wing. An early attempt to partner with a startup firm specializing in high efficiency cells (evaluated by SORSE at several NPS FX events) ended badly when the company went through an unfortunate collapse. Further attempts led to greater success. A vendor specializing in minimal encapsulation of research-grade mono-crystalline Si cells was located, and sample cells and small arrays were obtained for evaluation.

The cells are SunPower C60 bin-J cells, primarily used by solar-challenge participants, as they are too costly for conventional roof-top power generation. The cells are roughly 125mm square, with small corner losses. They are unusual in that the collector traces have been relocated to the backside of the cells, such that the entire front of the cell is an active collector. Advertised, un-concentrated efficiency is 22.5%, such that the cells with encapsulation nominally produce roughly 3.5W each.

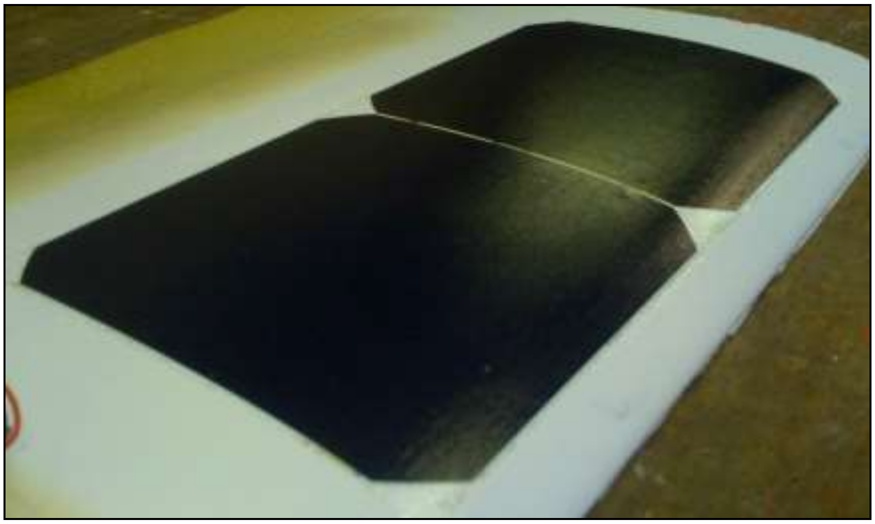

Figure 60. Wing sample with embedded SunPower C60 cells.

The cells are considered to be rigid, but if handled carefully they could be deformed significantly. A partnership was formed with the manufacturer of the glider airframe, R&R Products, and an effort was undertaken to attempt to integrate the cells into the wings during the original composite layup of the wing structure. It was felt that this would produce the smallest defects in the wing surface. In August a test sample of the wing (*see Figure 60*), upper surface with a two-cell array was delivered (*see Figure 61*), and demonstrated that the cells could be deformed sufficiently to conform to the airfoil surface to within a few centimeters of the leading edge. The company is in the process of installing an 18-cell array on a test wing which should nominally provide 63W, but in practice should be closer to 40-50W during daylight hours in the central California area.

Significant progress has been made in the electrical system design for the capture, storage, and release of electrical power, and MAE M.Sc. student LT Nahum Camacho (Mexican Navy) has been evaluating the system with a series of long endurance tests. The system includes a solar array (comparable to the one being installed on the aircraft), a combined maximum peak power tracker (MPPT) and charge controller, an array of rechargeable Lithium battery packs, and cell protection circuitry (*see Figure 64*).

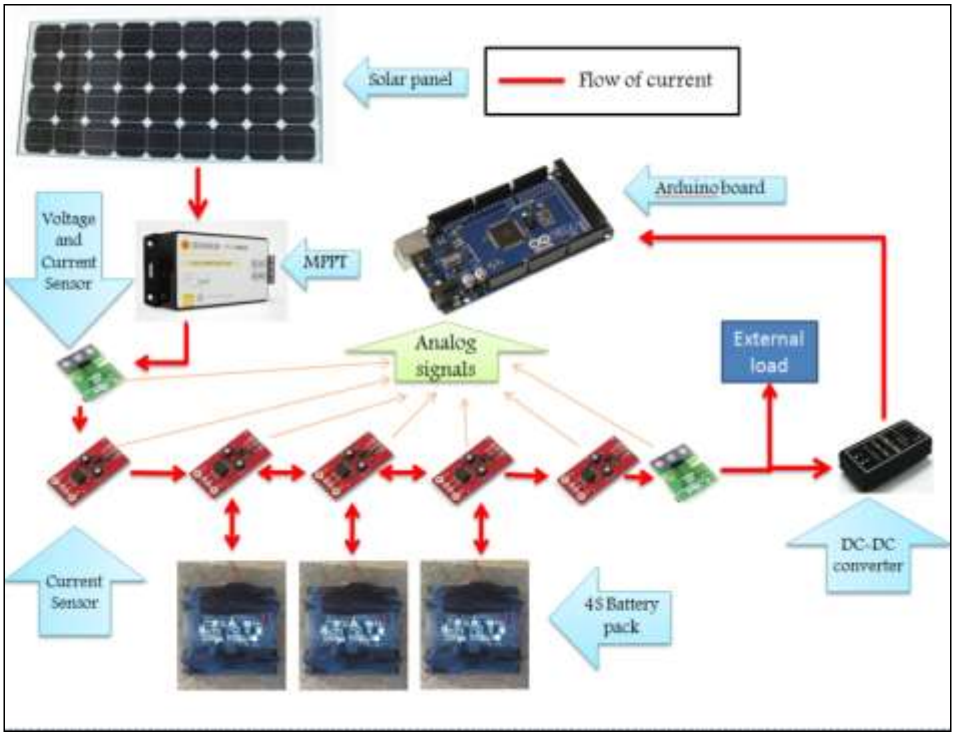

Figure 61. The electrical architecture for the solar-recharge system.

Photovoltaic cells typically produce a voltage and current that is related to the solar radiation and set by the impedance of the load. Power is the product of the voltage and current produced by the cell. The MPPT is a device that optimizes the impedance of the load in order to maximize power output from the PV cell. Output from the MPPT is a regulated voltage suitable for charging the Lithium batteries.

Generally, the preferred method of charging series lithium packs is to remove the packs from the asset and charge them in a safe place using a Lithium battery charger with cell-balancing circuitry to make sure the packs remain balanced. For TaLEUAS it is essential that charging take place on the aircraft during flight. Therefore, cell protection circuitry had to be included to prevent cell imbalance during repeated charge cycles on long endurance flights. Suitable circuits were acquired and completed the prototype electrical system.

A volunteer summer intern from UCSC, Kevin-Paxti Le Bras, developed an Arduino-based logging system and organized accompanying sensors to allow us to monitor/log voltage, current and temperature at any point in the electrical system. We assembled a test system using the small solar array, up to three battery packs and a nominal load, and measured voltage and current going to/from each component. LT Camacho leveraged the intern's efforts by developing a sensor-calibration scheme - vetted through several week-long roof-top tests to evaluate the system for maintaining an energy budget (*see Figure 62*).

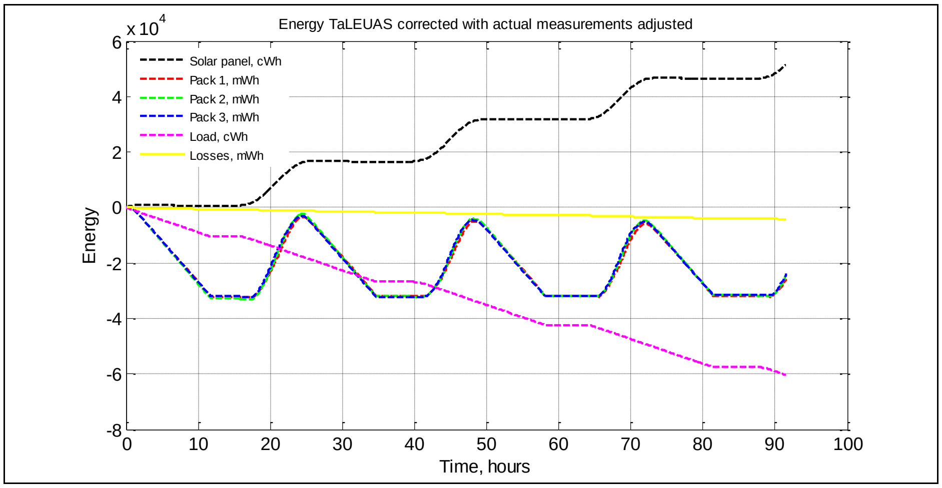

Figure 62. Results of multiple day test of solar management architecture in Figure 33.

This particular experiment began at night with the batteries fully charged. Therefore, that appears to be the zero-energy state for the batteries. During the night, the load slowly drains the batteries until the protective circuits cutoff power to the load. At that point the battery state is flat, as there is effectively no load, and there is no energy input from the array until the sun comes up. A somewhat more appropriate way to treat the battery state would be to consider the drained pack at its zero-energy state, and a charged pack at something above zero energy, as it chemically contains significant potential energy. Also, in flight the batteries can never be drained to the point of shutdown, as this will cut off power to the avionics, and we will lose the aircraft.

Battery selection and sizing was also a topic of interest this year. Most previous solar-powered aircraft studies have utilized Lithium-Ion cells comparable to those found in the average laptop, with the 18650 form-factor (18mm diameter, 65mm length, cylindrical cells). Cell manufacturers advertise a wide range of cell capacities, with energy densities ranging from 150Whr/kg up to 240Whr/kg. Unfortunately, these cells have relatively high internal resistances, and therefore have fairly severe discharge-rate constraints. Most limit the rate to 1C (1C equates to a full discharge in 1 hour). In theory, this should be fine for overnight flight, where the average discharge rate should be closer to 1/16C. Unfortunately, in practice, when the motor is intermittently used for propulsion at night, the discharge rates can be over 1C, perhaps as high as 3C. Our group has considerably more experience with LiPo batteries, which typically have lower advertised energy densities, but considerably high acceptable discharge rates (as high as 70C).

A series of drain tests were performed to compare Li-Ion cells with LiPo cells. The Li-Ion cells tested were Samsung ICR18650-30A, rated at 1C continuous, 2C burst, and the LiPo cells tested were the Advance Energy Inc. MS series, rated at 16C continuous, 30C burst. The test involved peak-charging the packs and then connecting them to a fixed load with logging equipment in place. The packs were drained to 3.2V/cell. Results for several cases are shown below (*see Figure 63*).

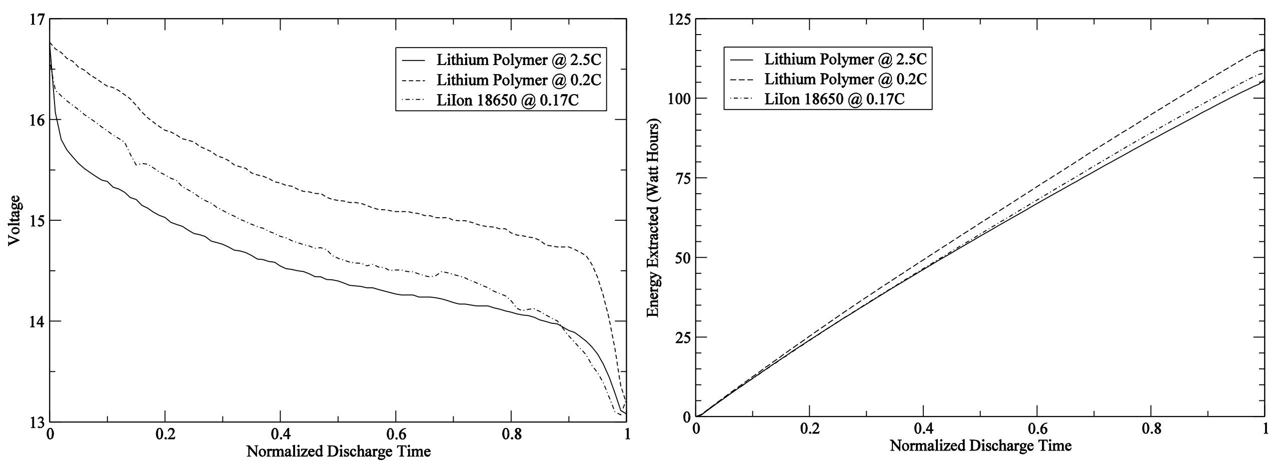

Figure 63. Battery discharge results for Li-Ion and LiPo packs.

In all cases, the voltage had “fallen-off-the-cliff” when the discharge was cutoff, meaning that virtually all of the useful energy in the cell had been depleted. The dependence of cell voltage and cell capacity on the discharge rate can be seen on the left and right, respectively. What is not apparent in the figures is that the Samsung cell advertises an energy density of over 230Whr/kg, but in the tests only produced

167Whr/kg. The Advanced Energy Inc. cells advertise a 190Whr/kg energy density (raw cell), and in the high-rate and low-rate drain tests had measured values of 178Whr/kg and 163Whr/kg, based on full pack mass. Based on these results, LiPo packs from Advance Energy Inc. have been selected for the first prototype. A pair of 4S (16.8v) 6000mAhr packs with built-in cell balancing circuitry will be utilized, and will serve both the avionics and propulsion requirements for the glider.

(b) Optimized Soaring and Cooperative Control Algorithms

Historically, several of the successful, smaller solar-powered aircraft were able to survive by using talented human pilots on the ground, to locate and utilize thermals for lift during the daylight hours.[26] This process allowed a large portion of the generated solar energy to go into battery charging rather than propulsion, giving the aircraft a better chance of surviving the night. TaLEUAS performs this difficult manual task autonomously, and as it turns out, as well or better than most human pilots can do. This capability is achieved by integrating a set of algorithms which allow the avionics to detect, track and characterize the thermal in 3D space. The knowledge gained about a particular thermal is geographically mapped and shared among multiple soaring aircraft to increase their cumulative energy harvesting capability.

While most of the existing techniques for autonomous soaring are based on precise knowledge of an aircraft and heuristic assumptions about the operational environment, the authors' prior experience in a related NASA-sponsored research project for fault-tolerant control suggests that this is not sufficient. Local flight conditions, uncertainty in the operational environment, and system degradation and/or failure all greatly affect the flight dynamics of the aircraft. When not properly accounted for, they adversely affect the expected performance of the aircraft and reduce the likelihood of success in projects such as this. Therefore, while adapting the conceptual ideas of traditional autonomous soaring, the approach used in our development shifts the focus from heuristics towards real-time estimation algorithms for the glider flight dynamics and the parameterized model of the convective updraft.

[26] Dornheim, M.A. (2005)

The algorithm for detecting a thermal is based on combining two complementary approaches – identification of the “natural sink rate in still air”, and “the total energy” approach. Both approaches are conceptually similar as they compare the natural metrics of the system with the same actually measured characteristics of the glider. The first approach utilizes the inherent sink rate polar and the second one is based on the total energy of the system.

Precise characterization of the sink polar (the function of vertical sink rate versus the true airspeed of the platform) of a particular glider can be practically achieved in extensive experimentation. However, flight-experimentation in the real-world environment can hardly provide ideal controlled conditions, and in every flight of the same platform there are always subtle differences that cannot be accounted for. Estimates of the sink-polar were made by post-processing a collection of experimental flight results obtained in low-wind, low-lift conditions. Sink polars are roughly quadratic in nature, and a least-squares approach yields suitable coefficients based on the historical data. In flight, a recursive least square (RLS) estimator may be used in real-time to account for specific variation in the platform and atmospheric conditions at that moment. The figure below (*see Figure 64*) shows this approach for a full-scale ASW-27 glider using the Condor simulator for the real-time flight data source.

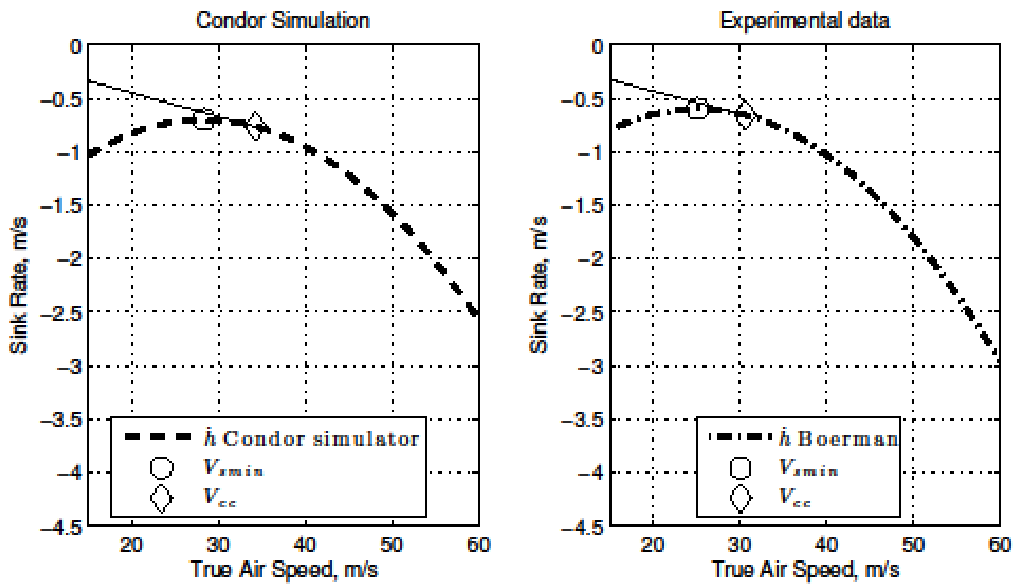

Figure 64. Comparison of the sink polar of ASW-27 glider with true data.

The algorithm for detecting a thermal compares the currently measured vertical speed of a glider with what the glider would have in conditions with no lift or sink - given by the sink polar. If the current sink rate is significantly lower than predicted by the sink polar, then there is a source of energy that moves the glider upward - the condition that detects the thermal (*see Figure 65*).

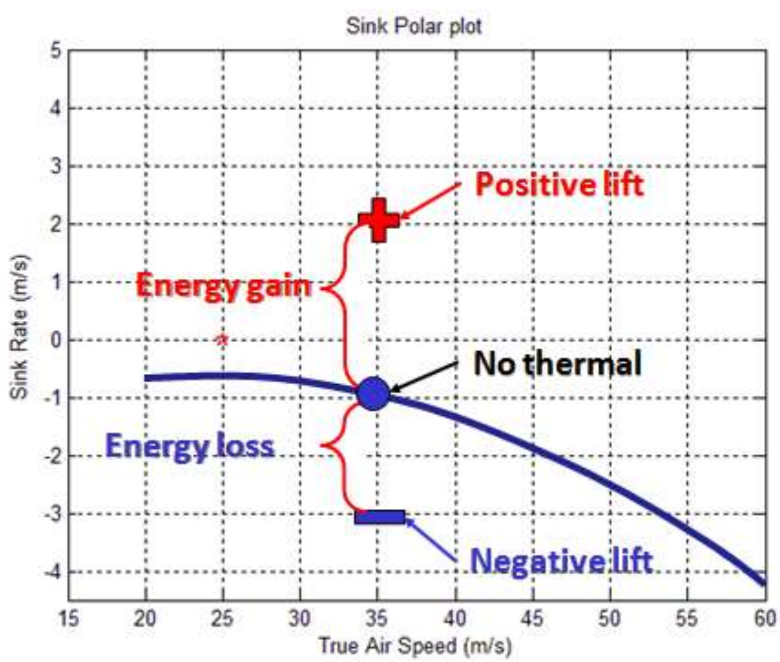

Figure 65. Detection of thermal lift based on sink polar.

The analytical representation of the sink polar significantly contributes not only to the identification of thermal updrafts but also to the mission planning of a specific glider. In particular, the polar defines the minimum sink rate velocity, V_{smin}, and the corresponding speed command for the autopilot to follow. While V_{smin} may be too close to the stall speed, V_{stall}, and should be avoided, the effective speed commanded in thermaling mode, V_{Th_cmd}, may be slightly higher. The polar also defines the optimal TAS command, V_{cc}, for the maximum glide ratio flight that is used by the navigation task in planning for a maximum range "cross-country" segment. While the sink polar is ideally obtained in a no-wind environment, its application to the known wind conditions is also straightforward and allows for the calculation of distances to be traveled in cross-country flight.

The total energy approach is also widely used in human piloted soaring flight. It is based on the concept that at any given time the mechanical energy, E_{tot}, of the soaring glider combines the potential energy, $E_{pot} = mgh$, and kinetic energy, $E_{kin} = \mathrm{m}V^2/2$, of the airframe minus the "leakage" of the energy due to the work of the parasitic and induced aerodynamic drag. For a relatively "clean" aerodynamic glider with an objective to minimize the total energy loss, the optimal control will necessarily result in mild variations of the angle of attack thus leading to the relatively constant parasitic drag. Thus, for highly efficient airframes the value of total energy remains nearly constant over long periods of time with its rate of change close to zero if there is no propulsion or external energy injected. As a consequence, in no updraft conditions the rate of change of the total energy is roughly zero. Therefore, if there is a significant variation of the total energy, then the energy rate will be significantly away from zero thus indicating the energy variation due to updraft or downdraft airflow.

The resulting energy-rate-based solution provides another precise indication of the updraft event. A comparison of the outputs of both approaches (sink polar vs. total energy) with the output of the total energy compensated variometer is presented in below (*see Figure 66*).

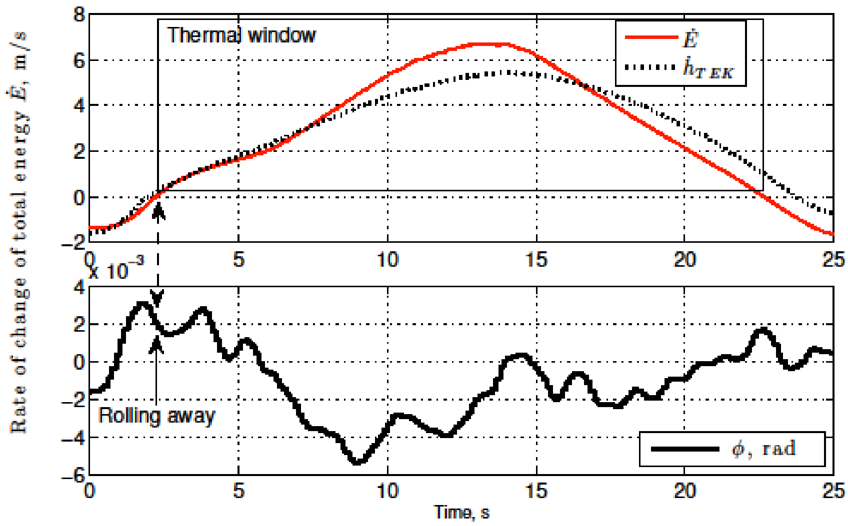

Figure 66. Comparison of two approaches to the detection of thermal updrafts

Thermaling guidance: The thermal centering guidance law that produces a turn-rate command to the autopilot is based on a feedback control law that takes into account the desire to get closer to the updraft center ($\rho \to \rho_d$), where its intensity (the vertical speed) is typically the highest, while simultaneously balancing the turn rate and the turn-induced sink rate by a measure proportional to the rate of change of the total energy variation (second time derivative of the total energy).

$$\dot{\psi} = \frac{V}{\rho_d} - k\ddot{E} \, .$$

The physical meaning of the guidance law is to increase the turn rate (typically implemented by the onboard autopilot through modifying the bank angle) until the rate of change of the increase of total energy is compensated by the sink resulted from the steep banking.

Cooperative thermal map building: The goal here is for multiple gliders acting cooperatively to be able to split up the search task for thermals, and share thermal location and characteristics data. As the number of gliders in the flock goes up, the knowledge of wide-area environmental conditions becomes increasingly well defined, and the probability of success for the full fleet asymptotically approaches 1. With a sufficient aircraft density in a region, a by-product of the flock's efforts to obtain free lift would be a meso-scale real-time meteorological map of the area.

Unfortunately, the filters developed in earlier work on this project were inherently independent. While the gliders did share predicted coordinates of a thermal at a particular location, that was the extent of the sharing, and no common model of the environment was formed. Further, in the past, gliders have not taken advantage of prior knowledge of the area either through recent meteorological surveys or historical data – where thermals have frequently been found in the past. Current efforts are using these to form a "heat-map" of sorts (*see Figure 67*), with layers depicting regions of high probability for a thermal at a particular time of day and/or time of year, and real-time data obtained within a short time-window of the present. The historical layer would be used when a flock moves from one location to another, and current data is not available, but current data will quickly be generated when they begin searching the area.

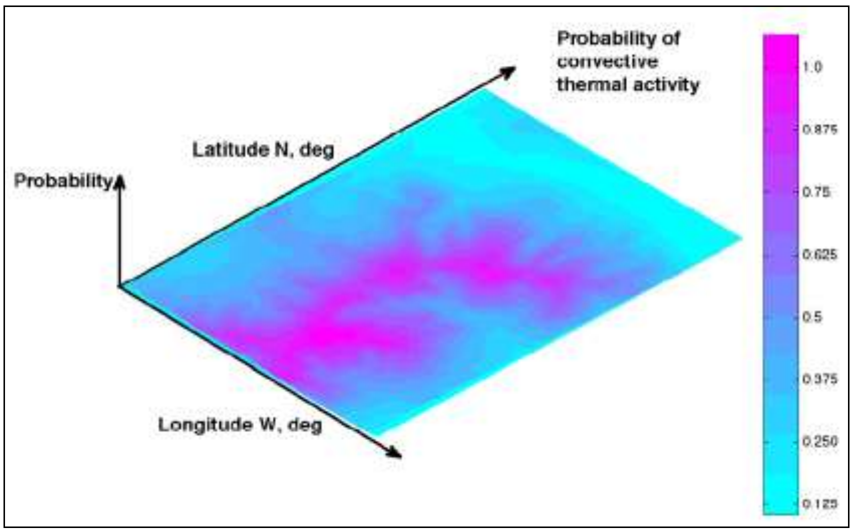

Figure 67. "Heat map" of probability of finding a thermal over an area of operation.

Therefore, to advance towards cooperative identification and mapping of thermals over an extended area with an account of prior methodological observation, the probabilistic recursive Bayesian approach was adopted. The results of cooperative thermal mapping were integrated into the navigation task solved for each glider. To achieve the mission objectives the geo-referenced thermals (sources of free energy) were used to guide the gliders toward the updraft on their way to the mission specified waypoints.

An example of the recursive Bayesian algorithm for the case of three simulated gliders flying cooperatively and estimating parameters of the same updraft is presented in the left figure below (*see Figure 68a*). In the demonstrated result the prior probability is initialized by a uniform probability density function that is defined as an inverse of the area of operation. This simulated the worst case scenario when there is no prior intelligence about the thermal activity in the area of operation. The result corresponds to the progression of probability estimated by glider #1, see the corresponding cooperative trajectories at the right (*see Figure 68b*).

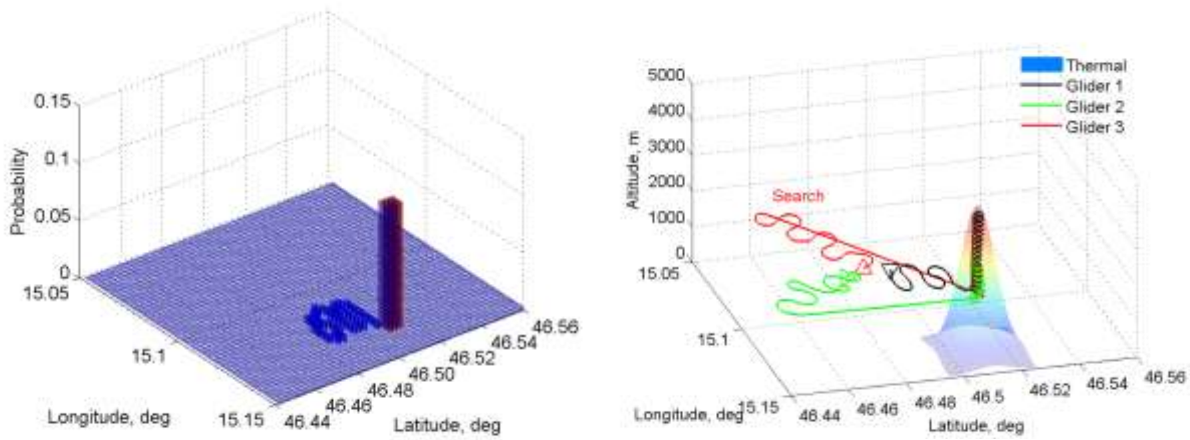

Figure 68. Cooperative navigation in the vicinity of strong updraft: *a* – recursive Bayesian estimation of thermal location, *b*- cooperative thermal exploitation.

To facilitate convenient design and verification of the designed algorithms the project also developed a realistic simulation environment that is based on tight integration of MatLab/Simulink capabilities with the high-fidelity flight dynamics and atmospheric effects of the Condor soaring simulator. Besides providing a wide nomenclature of gliders, the software is capable of integrating the cooperative behavior of human pilots that is essential to our project. The collaboration is enabled by sharing the states of gliders over the internet. Since the goal is to enable autonomous soaring and exclude the manual pilot command, the standard software was patched with an API (windows service) that enabled the reading of all states of the glider in a Simulink model and the sending of control surface commands from the cooperative soaring algorithms implemented by the MatLab/Simulink models. The architecture of the software in the loop (SIL) setup that integrates Condor with MatLab/Simulink is presented below (*see Figure 69*).

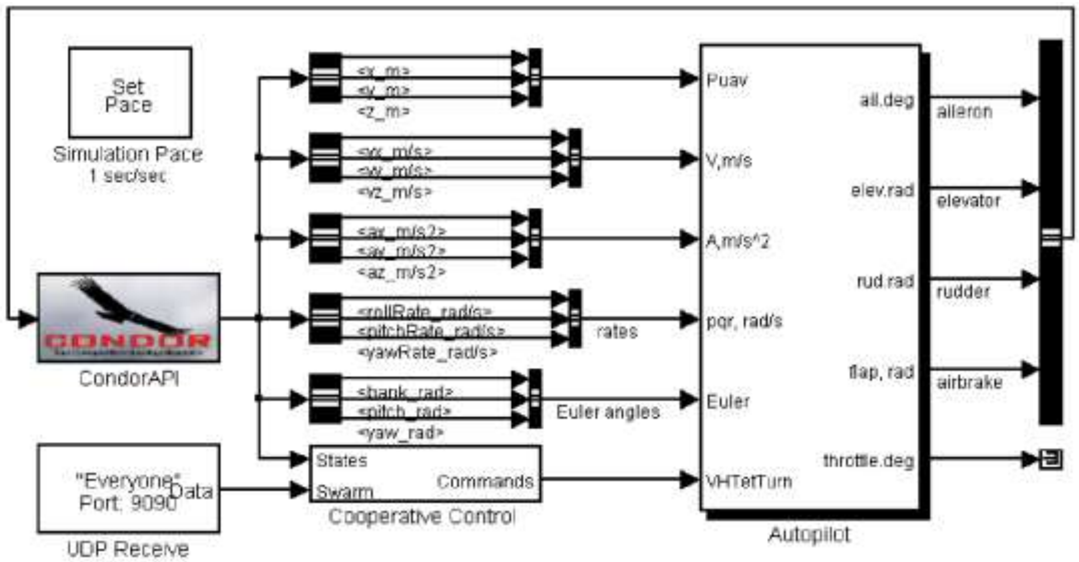

Figure 69. Integration of Simulink and Condor capabilities in high-fidelity SIL environment.

Several key contributions have been made on this front. The high-fidelity commercial full-scale soaring simulation code, Condor, has been adapted such that the NPS autonomous soaring algorithms can be used in the simulator to test our soaring skills against accomplished human operators. Additionally, the code allows for multiple autonomous gliders to cooperatively participate in the simulator, splitting up the search task, and sharing knowledge of thermal locations.

(c) Future steps

The future plans include the development in two primary directions. First is the design of novel distributed approaches for effective environment sensing and energy harvesting along with the cooperative mission management and execution algorithms. We envision that in an exemplary mission with the goal defined by the waypoints in the area of operation, the task of finding an optimal route for multiple "traveling salesmen" to visit all waypoints can be solved by weighting the edges of the underlying graph according to the proximity to the free energy sources in the area. Second is to develop a new hardware platform with high efficiency flexible solar panels integrated into the skin of the glider wings and the corresponding monitoring and the energy management algorithms. The task is underway with expected first flight of a single solar powered platform to be performed in February 2014.

POC: Kevin Jones (kdjones@nps.edu)

i. UAS Training and Pilot Certification Program

There is growing interest in Unmanned Aircraft System (UAS) research at NPS, but at present, there is no formal procedure for evaluating operator qualifications, in particular for vehicles that require a manual flight mode, or for evaluating UAS platforms for air-worthiness. The objective of this proposal is to work with the NPS ASO and the NPS FX program to develop a formal training procedure for both fixed and rotary-wing programs in order to evaluate and track operator competency, and develop a certification process for operators of systems that require a manual flight mode. There will be three major parts of the project. First developing the process for tracking UAS and operator qualification, second, developing a fleet of training aircraft (fixed and rotary-wing) and flight simulators to aid in pilot training and to evaluate operator proficiency in a safe manner, and third, to aid new research groups in developing SOPs and best practices for safe operations.

(a) FY13 Progress and Results

Listed deliverables for the project included a small fleet of RC aircraft suitable for flight training on fixed-wing, rotary-wing and multi-rotor platforms, flight-simulation hardware/software suitable for risk-free training on these configurations, and example SOPs for the fleet. The sections below detail the progress made in these areas.

There are currently seven aircraft in the test fleet, but more may follow as resources permit. Some were purchased directly under project funds, and others were essentially unused hardware from other programs that were donated to the cause. The fleet is briefly summarized below.

Fixed-Wing:

- Nano-Vapor: electric power, palm-sized, indoor aircraft (may be flown in the CAVR high-bay).

- Parkzone T28: small outdoor 4-channel trainer. Electric powered.
- Sig Kadet Senior: mid-size outdoor 4-channel trainer. Electric powered.
- Sig Rascal 110: Large outdoor, 5-channel. Electric powered

Rotary-Wing:

- Blade mCX2: palm-sized indoor coaxial, 4-channel helicopter (may be flown in the CAVR high-bay).
- Align Trex 600e: mid-size outdoor 5-channel helicopter. Electric powered.

Multi-Rotor:

- Blade MQX: palm-sized indoor quad-rotor. (may be flown in the CAVR high-bay).

Most of the fleet are flyable, although the outdoor fliers are currently grounded pending NOSSA battery approval. The indoor fliers may be flown for training at the present time. Several pilot handsets are available, including a Spektrum DX8 and a Spektrum DX-18. The two handsets have the option to be coupled for an instructor/student configuration known as a buddy-box. In this mode the instructor holds the master handset (the one with an RF-link to the aircraft), and can optionally allow one or more channels from the student handset to be passed through to the aircraft. The instructor can regain full control of the aircraft by merely touching any of the controls. The buddy-box system provides an excellent means to allow a student to learn to fly an aircraft while it is a safe distance from the ground, with the instructor taking-off and landing the aircraft. This system is suitable for fixed-wing aircraft, but more problematic for rotary-wing and multi-rotor aircraft. A better approach for them is stick-time on simulators and low-cost aircraft, possibly with training gear installed.

Under project funding a suitable laptop and several simulators were acquired. The laptop, a 17” HP, may be checked out for overnight/weekend use by interested parties. For best results, the laptop may be coupled to a large-screen TV for more realistic viewing. Two software packages are included, Phoenix and RealFlight. Both have comparable capabilities, but RealFlight tends to simulate fixed-wing aircraft more realistically, and Phoenix is better with helicopters. Both simulators come with specialized handsets, but both can be coupled to the Spektrum transmitters mentioned above for those interested in using the flight handset during simulation.

In preliminary discussions with other operators and the ASO, it is unofficially felt that simulator time, while immensely valuable for developing eye-hand coordination and piloting skills, should not be a substitute for real-life hands-on flight. Consequently, it is our believe that simulators should be used routinely to stay sharp and improve your piloting skills, but operator currency should be based on actual flight operations.

A binder with detailed fleet information, manuals, check-lists, ORM manuals, SOPs, and paper flight logs is being developed. The information for each aircraft will be required reading before use of the platform. In addition to these usual contents, an attempt will be made to include additional information about each aircraft with intent being to educate newcomers as to why something is done in a particular way. The goal of this is to educate by apprenticeship – offline. Historically, we have found groups attempting to get into this field that unfortunately didn’t have the necessary experience with the equipment and working environment to do it safely. Knowing and understanding best practices for the manufacture, maintenance and use of the platforms is a critical piece of ORM.

As an addition to the proposed deliverables, work has been done to develop a school-wide database for the purpose of tracking operator logs in a digital format. It is intended to track both pilots and GCS operators, and classify their participation as normal, instructor, or trainee. Further, the aircraft class is tracked, denoting fixed, rotary, or multi-rotor, and a size/weight class, and for pilots, the type of flying (single-aircraft, multi-aircraft, day, night, FPV, etc) is tracked. Not only is the database intended to provide a digital logbook for operators, but with appropriate rule-sets included, will allow the ASO and supervisors to verify currency of operators for a specific mission type, aircraft type, etc.

(b) The Way Forward

While much progress has been made this year, we are stuck at the moment at a critical juncture, where we have a fleet, but we cannot use it due to lack of NOSSA and perhaps NAVAIR approval. Most of a week was spent during the course of this project developing an SOP for Lithium battery use, with the intent of obtaining a green-box approval for smaller packs in the fleet of training aircraft as well as many of the research UAVs at the school from NAVSEA. Thus far, the green-box approval is still a dream. Further, it has become unclear if NAVAIR will stand by their earlier policy of not requiring IFCs for RC-type aircraft that fly under AMA rules.

When approval is granted, the fleet still needs to be test-flown and any bugs worked out. This will likely require trips to Camp Roberts, unless an exception to the controlled-airspace policy can be developed for flight at local model aircraft fields under AMA-rules. This would likely require a MOA with the local club, assuring them that NPS personnel are covered to AMA levels for liability in case of property damage and/or injury. Club fields are typically leased from the county, and the county requires liability coverage by all participants.

As time permits, one-on-one instruction is possible, both on the platform-development side, and the operator-skills side. Additional assets may be added to the fleet as needed or as they become available. While the operator-log database structure has been developed, the human interface still needs much work. It might be advantageous to write specification for the site, and then hand it off to ITACS for development, letting them host and maintain the site.

POC: Kevin Jones (kdjones@nps.edu)

j. Experimental Unmanned Aircraft System (UAS) Interim Flight Clearances

NPS Research and experiments involving flight test on UAS have been handicapped by delays and information requests related to the issuance of interim flight clearances (IFC). Much of the difficulties arise from the unknowns introduced by UAS compared to manned aircraft. An improved IFC system safety analysis process and toll set is needed to facilitate and enable the full spectrum experimental assessment of novel UAS and their potential missions. One proposed adjunct is a Bayesian Belief Network (BBN)-based tool for eliciting and analyzing UAS safety hazards.

(a) Project Progress And Status

This project was funded in June 2013. The funds expire 12/31/2013, and 44% of the budget is in the process of being obligated to retain a leading expert in the application of Bayesian belief networks (BBN) to aviation safety analysis and assessment. This assistance will contribute to development of a standardized tool to assure disciplined and consistent hazard analysis and safety assessment for NPS UAS flight testing.

By mid-July four Master's students were recruited from NAVAIR MSSE Cohort 311-123A to conduce a Capstone project to address the first phase of this project. A team website has been established to facilitate team collaboration; team members are located in Florida, New Jersey, California and the National Capital Region.

The team met with NPS stakeholders on 15 August 2013 and NAVAIR 4.0P, 4.1 and 5.0 stakeholders on 29 August 2013. These meetings revealed numerous concerns and practices that impede timely interim flight clearance (IFC). Issues ranging from related technical challenges, through systematic mismatches, to strategic considerations have been documented, widening the scope of our research. Initial documentation of NPS UAS flight test programs, venues and practices has been collected, with emphasis on anticipated Scan Eagle program plans.

Research into related literature, complemented by further discussions with concerned Navy personnel and industry contacts, progressed through September to clarify and document these issues and the viewpoints of the stakeholders. Preparation for the team's first interim progress review (IPR #1) continued through the end of September were somewhat delayed by furlough actions.

(b) Future Plans

IPR #1 was held 7 October 2013, identifying the perceived root cause and the research objectives, tasks & schedule. This was received well by the attendees and elicited more information on NPS concerns. Work has been initiated on modeling the NAVAIR IFC process, including consideration of its integration with the acquisition process focused on interactions with design & development and flight test practices and procedures.

POC: Richard Millar (rcmillar@nps.edu)

k. Maritime In Situ Sensing Inter-Operable Networks (MISSION)

Maritime domain awareness (MDA) and undersea warfare (USW) are national security imperatives that can be served by the deployment of underwater autonomous sensors and systems. Project k. Maritime In Situ Sensing Inter-Operable Networks (MISSION) is advancing acoustic communications (acomms) and networking technology to enable such underwater distributed wireless architectures (*see Figure 70*). Project MISSION is emphasizing operations in noisy littoral environments and is fostering cross-nation interoperability. Project goals include:

- Study noisy underwater environments
- Achieve acomms through adverse channels
- Obtain datasets for acomms channel studies and transmission security (TRANSEC) studies
- Integrate U.S. Seaweb and Singapore Unet networks
- Demonstrate acoustic networks in Singapore Strait
- Enable distributed wireless architectures for MDA and USW

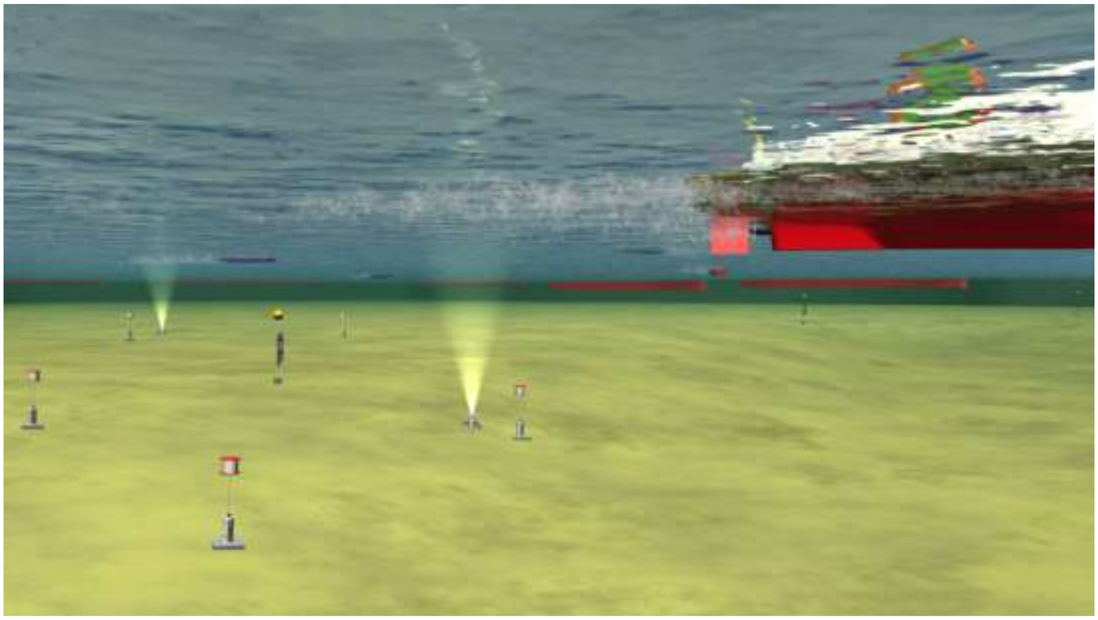

Figure 70. Project MISSION involves the collaborative testing of NPS Seaweb and NUS Unet underwater acoustic networks in the shallow (15-40 meter), noisy waters of Singapore Strait. MISSION experiments were conducted in October 2012 and November 2013.

Project MISSION is formally established by Navy International Programs Office (NIPO) and Office of Naval Research (ONR) for collaborative research by CRUSER at NPS and National University of Singapore (NUS) Acoustic Research Laboratory (NUS ARL). Co-Principal Investigators are Professor Joseph Rice of NPS (Monterey, CA), and Mandar Chitre of the National University of Singapore. ONR 32 and CRUSER each provide matching funds for the U.S. MISSION activities, and Singapore Ministry of Defence (MINDEF) sponsors the Singapore national participation. Moreover, Singapore is hosting the MISSION experiments in Singapore Strait and is providing ship support, logistical support, and environmental compliance support.

Figure 71. Faculty and students perform acoustic communications experiments in Del Monte Lake on the NPS campus and in adjacent Monterey Bay.

In keeping with the CRUSER charter, the CRUSER investment in Project MISSION is directed toward education and research on the NPS campus, including procurement of equipment, operation of facilities, and work performed by NPS faculty and students. Specific CRUSER expenditures include acquisition of test instruments, establishment of on-campus Seaweb laboratories, preparation and operation of an on-campus test site at Del Monte Lake (*see Figure 71*), engineering testing on the bench, project-relevant labor and travel, funding for student research, and expenses associated with conference presentations and publications. The ONR funds issued to NPS largely cover the contributions by contractors Teledyne Benthos, Inc. and Liquid Robotics, Inc., and engineering support by SPAWAR Systems Center Pacific.

With cooperation by the Physics Department and the USW Research Center, Project MISSION established the NPS Seaweb Lab in Spanagel Hall. A series of in-water experiments performed in Del Monte Lake and in Monterey Bay have supported student thesis research and Seaweb engineering tests. In addition, a May 2012 acoustic survey jointly conducted by NPS and NUS in Singapore Strait established baseline metrics for MISSION experimentation in that challenging environment.

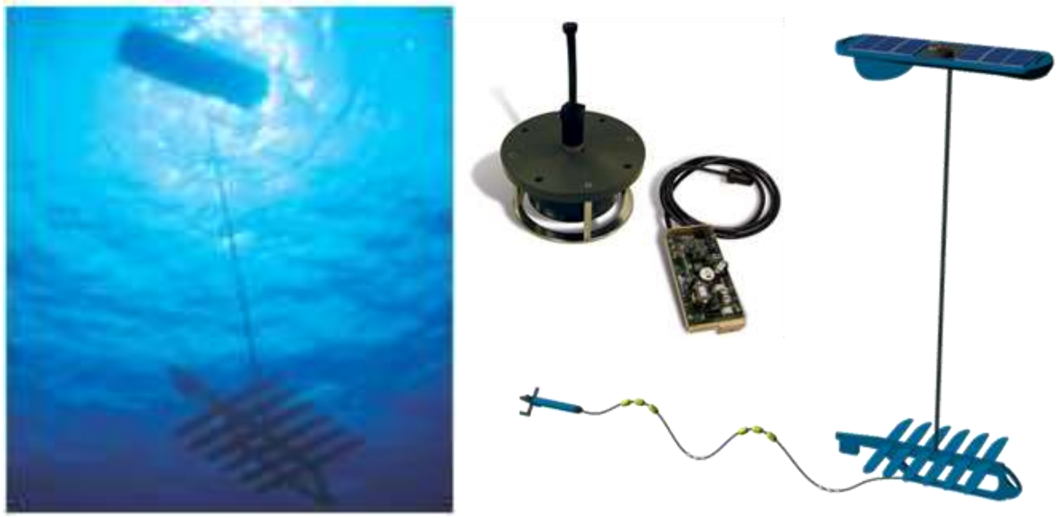

Figure 72. The Wave Glider USV (left) converts vertical sea surface motion into forward thrust. It captures solar energy to power on-board navigation, sensing and communications. Project MISSION has integrated an acoustic modem (electroacoustic transducer and electronics board shown) with a tow body compliantly attached to the lower body of the Wave Glider (right). The resulting "gatekeeper" station-keeping gateway node provides the critical communications interface between the underwater Seaweb network domain and the space-borne Iridium satellite communications domain.

(a) Project MISSION implementation

A longstanding issue with underwater networks is the vulnerability of moored gateway nodes at the sea surface. Project MISSION is exploring the feasibility of using an unmoored unmanned surface vehicle USV as the gateway node. The Seaweb Lab has acquired two Wave Glider USVs as experimental platforms for the advancement of a station-keeping, unmoored gateway node to provide the critical interface between the Seaweb underwater domain and the above-water Iridium satellite domain (*see Figure 72*). LT Tim Rochholz, USN, considered the practicality of persistent station keeping by the Wave Glider against the external forces of ocean currents and wind. To gain insight, he followed the progress of four Wave Gliders during the first leg – from California to Hawaii – of the historic PacX trans-oceanic crossing. ENS Joe Beach, USN, studied the engineering tradeoffs arising from the addition of an acoustic modem to a Wave Glider USV. He considered the impact of hydrodynamic drag and the acoustic performance of the modem for candidate locations on the Wave Glider USV. NPS has collaborated with industry partners Liquid Robotics, Inc. and Teledyne Benthos, Inc. to develop a towed acoustic modem integrated with Wave Glider electronics and Iridium modem.

Project MISSION acquired a pair of modem-recorder instruments incorporating a digital recorder with an acoustic modem to facilitate acoustic data acquisition and *in situ* underwater signaling measurements (*see Figure 73*). Secure digital (SD) memory cards, electronics, and battery pack are housed in a pressure-tolerant glass sphere with a penetration for the cylindrical electroacoustic transducer. These modem-recorders are useful for performing controlled soundings of the acoustic channel. Acoustic modems in the network are commanded to transmit a suite of experimental waveforms and channel probe signals following an experimental method known as Signalex involving parametric analysis of signals and careful measurement of environmental factors. Signalex transmissions are received by the modem-recorder instruments and enable analysis of the channel scattering function and link margin. Such in situ measurements are supporting the development of physics-based propagation models, adaptive modulation, and TRANSEC.

Figure 73. Modem-recorders are housed in pressure-tolerant glass spheres for deployment at depth. Received acoustic signals are digitally recorded to removable SD cards for later analysis.

Project MISSION permits researchers to study noisy and variable acoustic communication channels, perform collaborative studies, and conduct long-duration in situ measurements. The Seaweb Lab, Wave Glider USVs, Del Monte Lake, modem-recorders, and the pre-existing inventory of Seaweb acoustic modems and underwater sensors are providing the basis for MISSION experiments in Singapore Strait during October 2012 and November 2013. The MISSION experiments provide opportunities to test channel-tolerant and channel-adaptive acoustic communications, and enable the project team to conduct controlled signaling experiments in acoustically challenging and operationally relevant littoral environments.

Singapore is a challenging environment for underwater communications because of strong tidal currents, shipping noise, and biological noise (snapping shrimp). NUS has developed underwater modems that have been optimized for performance in Singapore waters. These modems can provide short-range links (in a local-area network) to complement the Seaweb medium-range modems (in a wide-area network). An experimental goal of the MISSION collaboration is to demonstrate interoperable communications between a Singapore Unet LAN nested within a U.S. Seaweb WAN.

Additionally, NPS is party to a NATO Joint Research Project (JRP) advancing Next-Generation Autonomous Systems (NGAS) for Anti-Submarine Warfare (ASW) surveillance. Through the NGAS JRP, Project MISSION participated in a 2-week sea trial in Oslo Fjord, Norway during October 2012 and in a 2-week trial in Halifax Harbor, Canada during September 2013. These international sea trials in diverse environmental conditions exercised U.S. Seaweb technology as the underlying communications network integrating a heterogeneous set of experimental underwater ASW surveillance sensors being developed by NATO partners Defence R&D Canada (DRDC Atlantic), Germany Federal Armed Forces Underwater Acoustic and Marine Geophysics Research Institute (FWG), Norway Defence Research Establishment (FFI), and U.S. Space & Naval Warfare Systems Center (SSC Pacific).

NPS Project MISSION investigators are contributing knowledge and technology to various U.S. Naval programs, including the Deep Seaweb JCTD, the PMW 770 Undersea Connectivity Roadmap, and the OPNAV N2/N6 Undersea Distributed Network.

(b) Project MISSION experimentation in Singapore Strait, 2012

Project MISSION has advanced through-water acoustic communications and networking capability with emphasis on cross-nation interoperability in noisy littoral environments (*see Figure 74*).

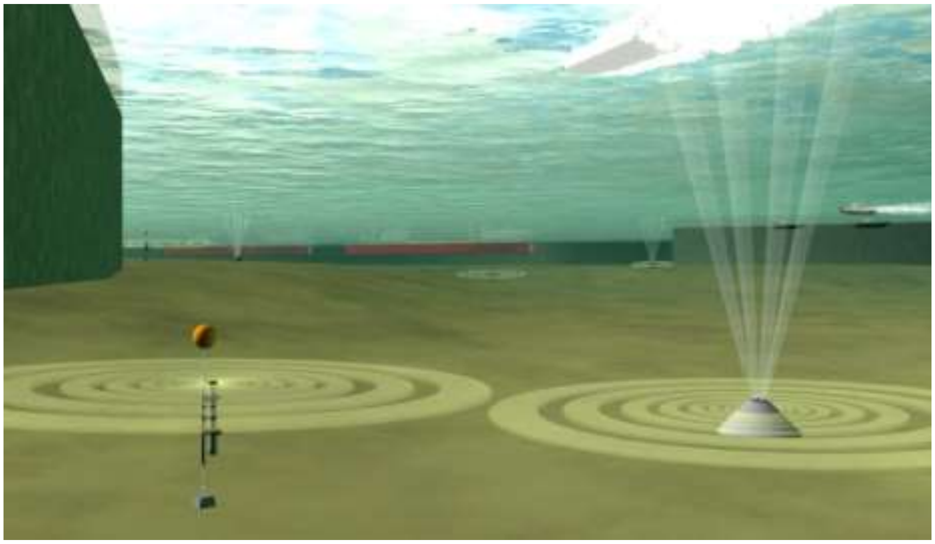

Figure 74. Maritime In Situ Sensing Inter-Operable Networks (MISSION) deliver near-real-time data from distributed underwater sensor stations.

Figure 75. The site for MISSION 2012 and 2013 sea trials is a waiting basin for container ships adjacent to the port of Singapore (background waters), and the Singapore Strait (foreground), a vital sea lane connecting the Indian and Pacific Oceans. The NUS Research vessel *Galaxea* supports all aspects of testing.

NPS and NUS performed the 3-week MISSION 2012 trial in Singapore Strait during October 2012 (*see Figure 75*). MISSION 2012 achieved the following objectives:

- Operated 10-node Seaweb wide-area network in noisy, high-current waters for duration of trial.
- Exercised linear network with 8 hops and 556-byte data packets.
- Deployed data-recording telesonar testbed as a surrogate interceptor.
- Recorded 24 hours of intensive network activity for link margin and TRANSEC analysis.

- Performed network discovery and autonomous initialization of network routes using cost function optimized to favor r=500m links.
- Operated 5-node Unet local-area network.
- Tested Unet modem software.
- Evaluated ranging performance.
- Measured variability of communication channel (eigenray propagation and noise).
- Observed in-band ambient noise and its relationships to external factors (diurnal cycle, rain, wind, shipping, etc.).

The figure below (*see Figure 76*) is a representative channel scattering function showing the instantaneous channel response observed at MISSION 2012.

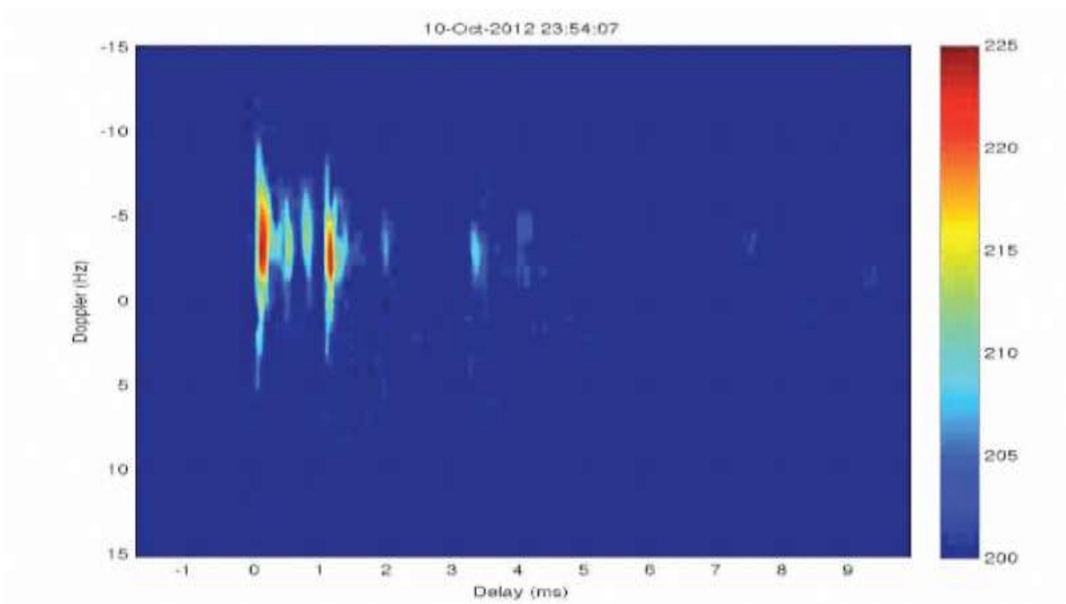

Figure 76. Instantaneous channel response observed at MISSION 2012 is represented by the channel scattering function. The transmitted signal is spread in time by multipath and scattering. The received delay is represented by the x-axis of the channel scattering function. The transmitted signal also experiences Doppler spread, represented by the y-axis, largely imparted by the moving sea surface. This example exhibits 2 dominant multipaths and significant Doppler spread. MISSION data recorded in Singapore Strait exhibit time-varying channel scattering functions that impair communications in terms of energy spread and inter-symbol interference. The underwater acoustic channel must be well understood in the design of channel-tolerant or channel-adaptive modulation.

(c) Project MISSION 2013

MISSION 2013 is the second in the series of bilateral experiments involving NUS and NPS. MISSION 2013 continues the NUS-NPS collaboration and builds on results achieved in 2012, extending the state of the art of underwater acoustic channel measurements, communications, and networking. The U.S. objectives at MISSION 2013 include:

- Exercise and stress Seaweb network containing at least 10 fixed nodes.
    - Demonstrate autonomous discovery, ranging, and routing.
    - Scripted exfiltration of large (4-kByte) data packets from distant source node via multi-hop route to gateway node for extended periods (overnight and weekends).
    - Record acoustic network activity for TRANSEC studies.
    - Optimize link-layer timers, MMP, binary and ASCII data packets, Word utility packets.
    - Stress network capacity with multiple source nodes to test Neighbor-Sense Multiple Access (NSMA) collision avoidance.
    - Characterize and document any instances of modem reboots.
- Obtain comprehensive networking data sets.
    - Synchronize Seaweb nodes at start of test; measure clock drift at end of test.
    - Log all modem comms internally.
    - Log all comms at server.
    - Compile comms statistics (packet size, SNR, AGC, RTS attempts, SRQ attempts, dropped packets, network latency).
- Co-locate USA Seaweb and SIN Unet gateway nodes at barge.
    - Co-locate USA and SIN transducers on a shared frame.
    - Implement independent gateway node cabling, electronics, and user interfaces.
- Demonstrate USA:SIN interoperability.
    - Implement Application Programming Interface (API) at topside workstations.
    - Pass data packets from Singapore LAN to Seaweb WAN.
    - Pass data packets from Seaweb WAN to Singapore LAN.

- Implement Seaweb server improvements.
    - Exercise ASCII and binary messaging.
    - Implement upgrades to time-stamped database of network activity.
    - Improve graphical user interface (GUI).
- Perform Signalex data collection.
    - At least 10 transmit locations.
    - At least 2 receive locations.
    - For environmental noise studies.
    - For channel multipath characterization and statistical stationarity studies.
    - Updated "autobaud" command for automated transmission of standard modulations.
    - Experimental waveforms (.wav files) in the 9-14 kHz band.
    - For power-control studies (6.1).
    - For adaptive-modulation studies (6.1).
    - For TRANSEC studies (6.2).
- Test network routing involving mobile gateway.
    - Drifting vessel with deck box and Seaweb server.
    - Exploit tidal current for drifting gateway platform.
    - Demonstrate cellular addressing and cell handoff as mobile gateway migrates from cell to cell.
    - Single and dual gateway operations.
- Demonstrate hardware and operations to interested visitors.

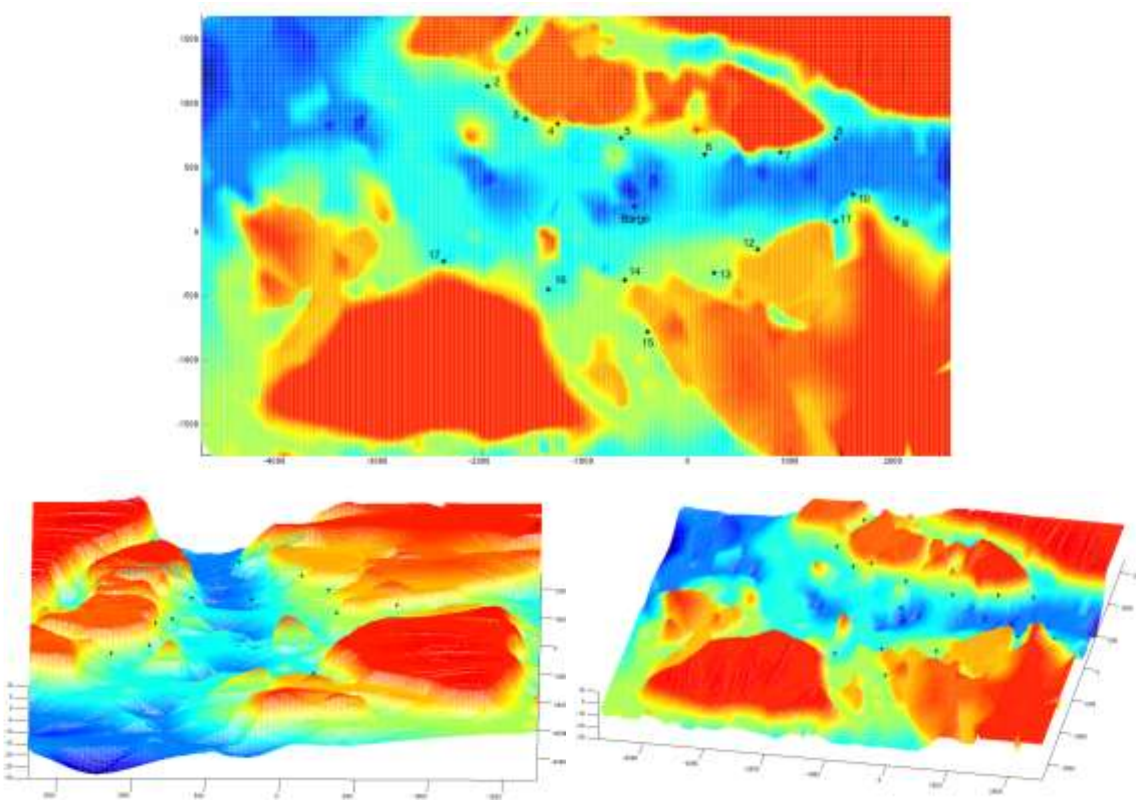

Figure 77. Underwater network nodes at MISSION 2013 are deployed at 18 stations approved by the Singapore coast guard (MPA). These are shown with respect to water depth in plan view (*above*) and in perspective view from west and south (*below left and right, respectively*).

The Singapore objectives at MISSION 2013 (*see Figure 77*) include the following:

- Study underwater noisy environments.
    - Measure variability in acoustic channel using probe signals.
    - In-situ delay-Doppler analysis.
- Achieve communications through adverse channels.
    - Test link tuning algorithms & implementation.
- Integrate U.S. Seaweb and Singapore Unet networks.
    - Seaweb-Unet integration tests.
- Demonstrate in situ environmental and surveillance sensor networks in Singapore straits.
    - Test ship tracking capability of network.
- Enable distributed wireless architectures for maritime domain awareness and undersea warfare.
    - Test automated network route discovery.

- Test automated network self-localization.
- Test navigation, tracking & communication to STARFISH over Unet network.

- Collect environmental data on tides, currents, waves, temperature, salinity and ambient noise.
  - Environmental data collection.
- Develop shallow water acoustic communication model for experimental site and validate using experimental data.
  - Experimental validation of acoustic modeling.
- Develop 3D particle tracking module to predict trajectories of mobile communication nodes and validate using experimental data.
  - Collect data for testing of AUV motion model based on currents.
- Test energy efficient mission planning.
  - Collect current data for energy efficient mission planning.
  - Test energy efficient mission planning using STARFISH.
- Test advanced Unet algorithms, modulations and protocols.
  - Test FH-BFSK performance of Unet modems.
  - Collect data for sparse equalization of single carrier and multi-carrier communications.
  - Test partial FFT based OFDM.
  - Test network coding based broadcasts.
  - Test Doppler estimation and compensation.
  - Test J-ARQ performance.
  - Test super TDMA implementation.
  - Test remote file transfers.

    Test MACA and ALOHA-ACS performance.

Project MISSION concludes December 31, 2013. It leaves an unprecedented archive of acomms and underwater networking data for use in future studies of channel variability, adaptive modulation, TRANSEC, and the effective application of acoustic communications networking to achieve distributed underwater systems. Moreover, direct participation in these experiments has significantly advanced the state of art of U.S. Seaweb and Singapore Unet underwater networked communications.

POC: Joe Rice (jarice@nps.edu)

2. Office of Naval Research Reserve Component (ONR-RC) Unit 113 Relationship

Building on an association established in FY12, CRUSER has strengthened and formalized an ongoing relationship with Office of Naval Research Reserve Component (ONR-RC) Unit 113. CAPT David Harach, who serves as Commanding Officer of the unit and Program Lead for CRUSER activities, again spent time in residence at NPS to support CRUSER. CAPT/Dr. Harach also serves as Senior Materials Engineer at the NAVAIR Materials Engineering Laboratory at Fleet Readiness Center Southwest in San Diego CA.

The mission of ONR-RC is to leverage unique Navy Reserve capabilities to help ONR and the Naval Research Laboratory (NRL) provide science and technology solutions to the warfighter. The primary mission of the fifteen ONR reserve units is to supply a cadre of uniquely qualified individuals for project work. ONR/NRL S&T 113 Unit leads ONR-RC Unmanned Vehicles (UV) Focus Area, responsible for all ONR-RC direct support to ONR on UV research and development, project support, and fleet introduction of critical UV emerging technologies. ONR/NRL S&T 113 is operationally assigned to support ONR-funded projects at NPS.

ONR/NRL 113 has supported many NPS projects in recent years, and CRUSER is a growing project support area. Recently, three unit members worked with NPS Systems Engineering Professor Dr. Timothy Chung and his colleagues during his Advanced Robotic Systems Engineering Laboratory (ARSENL) Swarm UAV field experimentation and flight testing at Camp Roberts. Reservists refined flight preparation, launch, and safety checklists; and began the design of pilot and aircraft logs. The assistance provided by ONR reservists significantly reduced the interval between aircraft launches, and resulted in a new NPS record for UAVs airborne at one time. This collaborative effort is scheduled to continue as Dr. Chung expands his flight test program.

POC: Dr. David Harach (david.harach1@navy.mil)

D. EXPERIMENTATION

CRUSER-affiliated NPS faculty and students continue to engage in their own unmanned systems experimentation, and participate in outside experiments and tests. CRUSER funded field experimentation in FY13 included:

- QR Codes (*see report section II.C.1.b*) **POC:** Dr. Don Brutzman (brutzman@nps.edu)
- Swarm versus Swarm (*see report section II.C.1.d*) **POC:** Dr. Timothy Chung (thchung@nps.edu)
- Maritime In-Situ Sensing Inter-Operable Networks (MISSION) (*see report section II.C.1.k*) **POC:** Professor Joe Rice (jarice@nps.edu)

Aligning parallel efforts and sharing research updates among a greater community of interest through CRUSER has magnified the benefits of these formerly disparate experimentation efforts. Current NPS field experimentation efforts take place regularly at Camp Roberts, an hour drive south of the NPS campus in Monterey. Two of the CRUSER sponsored projects conducting experimentation in FY13 were part of the first programmatic Innovation Thread started in September 2011, and one was ongoing cooperative research with ONR.

E. OUTREACH

1. Community of Interest

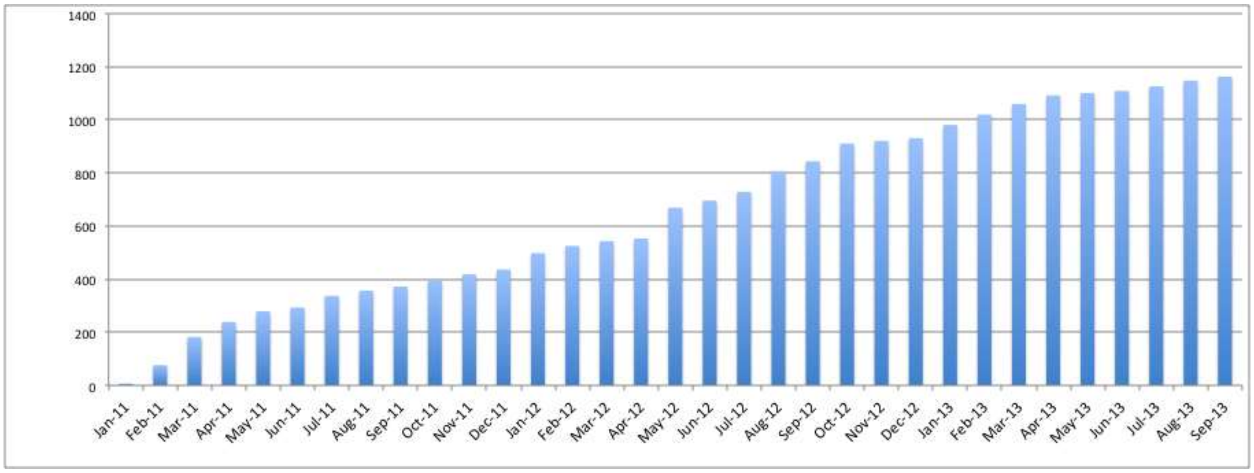

Figure 78. CRUSER community of interest growth from January 2011 to September 2013

At the end of FY11, CRUSER's first program year, the CRUSER community of interest had grown to include almost 400 members. As of 30 September 2013 this fledgling community consisted of 1165 members (*see Figure 78).* 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 79*).

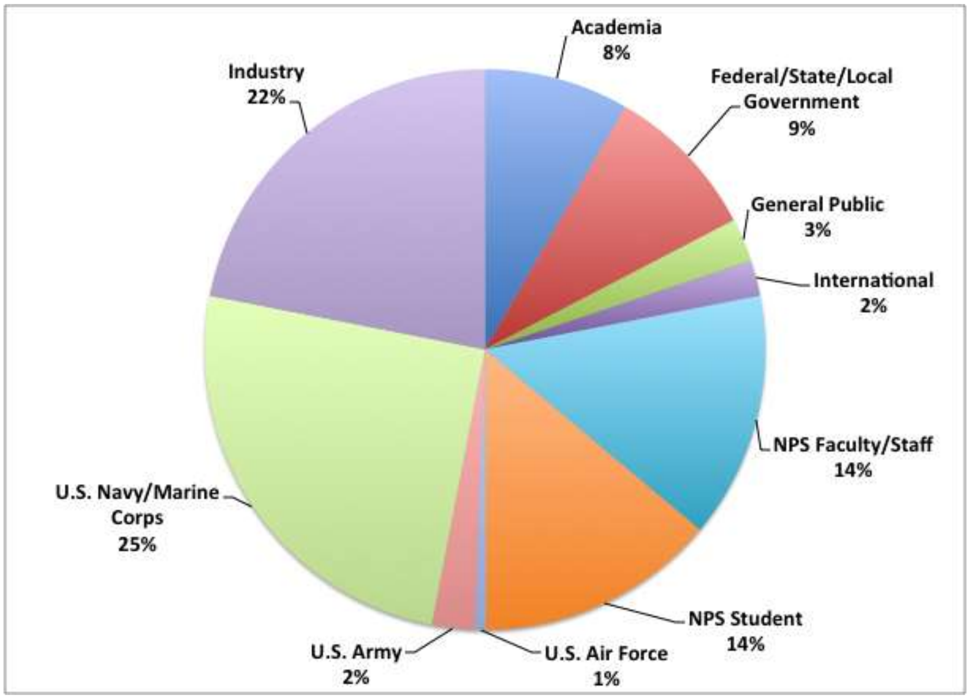

Figure 79. CRUSER community of interest breadth of membership, September 2013

Thanks to the outreach efforts involved with the 2nd Annual Robots in the Roses Research Fair in May 2012, the CRUSER community now includes a number of secondary school students and faculty who are integral in bringing the next generation of thinkers into the emergent field of robotics research and experimentation (*see Figure 80*).

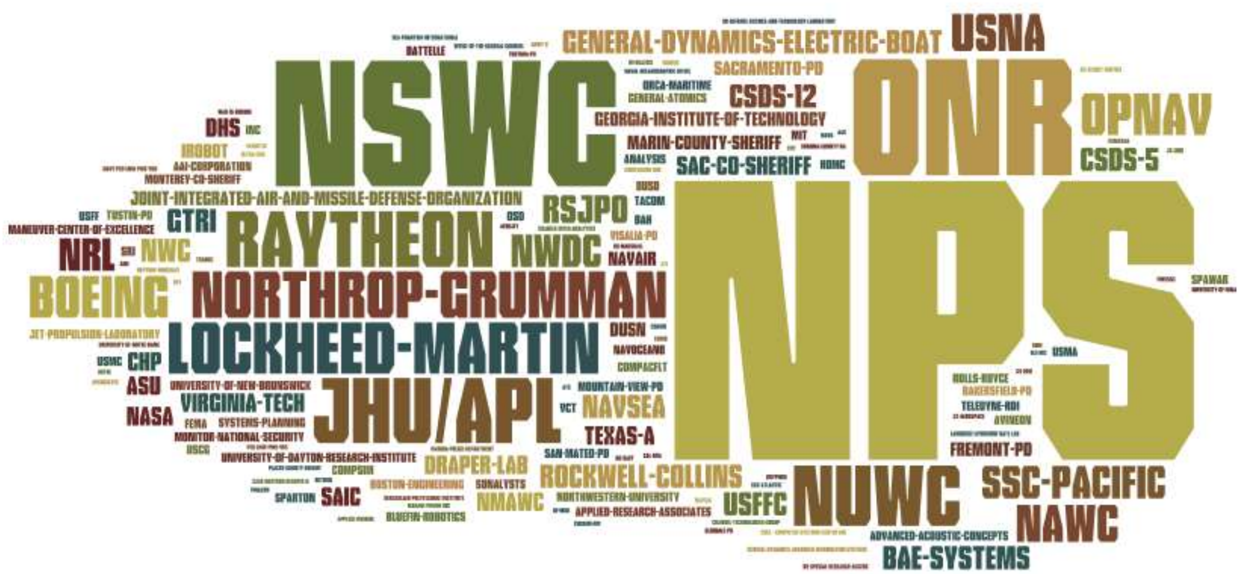

Figure 80. CRUSER community of interest membership roster word cloud, September 2013

CRUSER continues to produce a monthly newsletter, and accepts article submissions from the entire community. This four page document is sent electronically each month to the entire community distribution list, and just distributed Issue 31 on 15 September 2013. Additionally, CRUSER holds a monthly community meeting on the NPS campus (*see Figure 81*).

Figure 81. CRUSER monthly meeting in progress, September 2013

Non-resident members may join the meeting by phone, video, or using the campus distance learning tool Elluminate.

2. Briefings

As in past years, the CRUSER leadership team continued to meet a steady request for briefings on the program by visiting representatives of industry, academia, other DoD commands, as well as international military visitors. A representative listing of CRUSER briefings is included in Appendix B of this report. Most briefings were delivered on the NPS campus in the CRUSER Coordination Center, although CRUSER briefings were given in other campus locations as well as offsite.

3. Student and Faculty Travel

CRUSER supported a several NPS student trips in FY13 to further their thesis work (*see Table 8*). NPS students were then required to give a trip report at a monthly NPS CRUSER meeting to further socialize their work.

Table 8. CRUSER funded student and faculty (*) travel, FY13

Date	Student	Description
January 2013	LT Joshua Weiss	Visit Deep Submergence Unit and Undersea Rescue Command for briefing
January 2013	LT JB Zorn	Thesis research – site visit
May 2013	Nahum Camacho Jeremy Joseph Fabian Loy	Field experimentation
May 2013	Marianna Jones* Dr. Kevin Jones*	Black Dart
June 2013	Nahum Camacho Fabian Loy	Field experimentation
June 2013	Ryan Wodele	Thesis work
June 2013	Dr. Tim Chung* Dr. Kevin Jones* Michael Day* Marianna Jones* Carson Vogt (*intern*)	Field experimentation
July 2013	Four USNA MIDN (*CRUSER Scholars*)	Research assistance at NPS
August 2013	Jeremy Joseph	Field experimentation
August 2013	Matt Epperson (*intern*) Carson Vogt (*intern*)	Field experimentation
August 2013	Marianna Jones* Dr. Tim Chung*	Black Dart
September 2013	LT Ryan Hilger	Field experimentation
September 2013	LT Andrew Streenan	Field experimentation

Travel for faculty members to participate in research opportunities was also supported (*noted in Table 8*). CRUSER also supported travel for four USNA Midshipmen to participate in NPS research projects in July and August 2013. CRUSER will continue to support student and faculty participation in unmanned systems related conferences on an ongoing basis.

III. CONCLUSION

The overarching CRUSER program Innovation Threads (*see Figure 82*) give a broad overview of programming themes through FY13, starting in September 2011 with the CRUSER WIW concept generation event – the start of program Innovation Thread 1. Program Innovation Thread 2 began with the CRUSER September 2012 WIW and continues concurrently as Innovation Thread 1 moves through field experimentation in early FY13. Both threads will end with unmanned systems exposition events in Washington DC, in June 2013 and June 2014 respectively. Innovation Thread 3 just began with the concept generation workshop in September 2013.

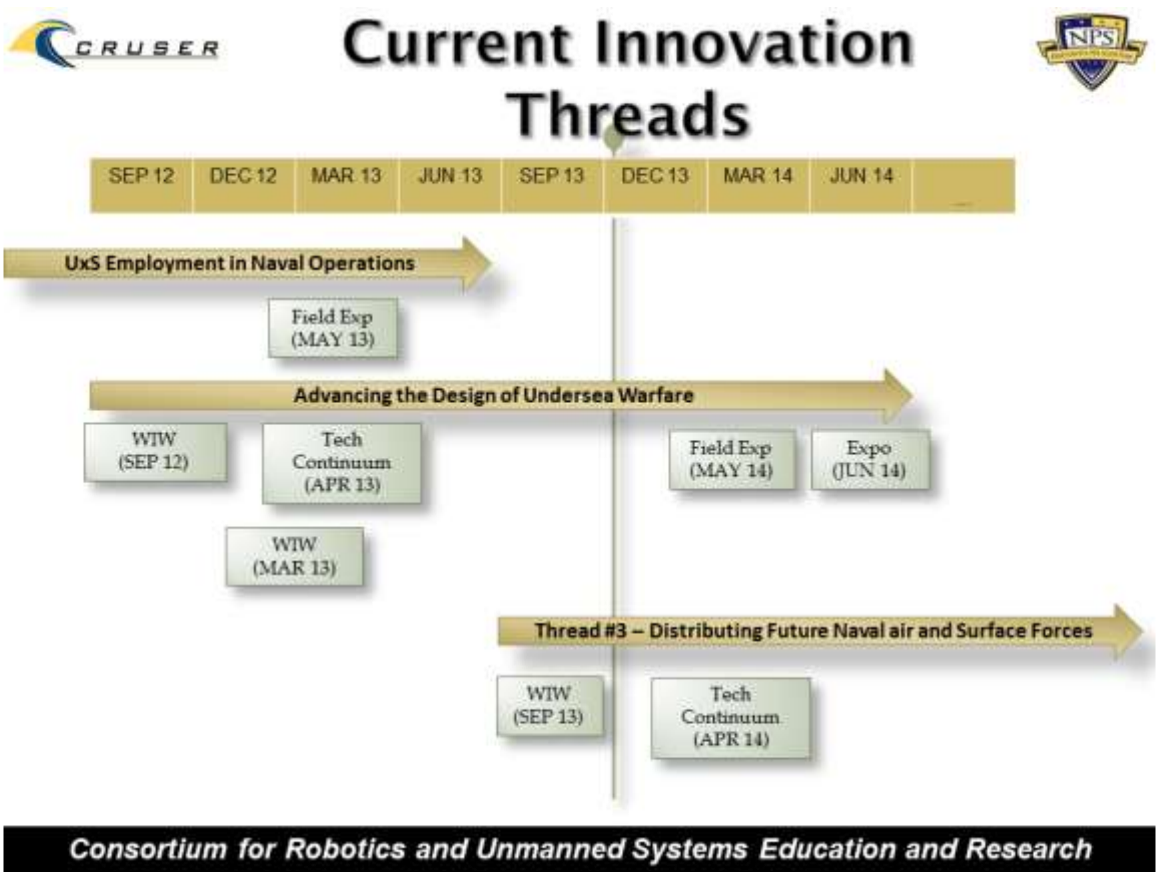

Figure 82. CRUSER Innovation Thread overview, September 2013

A. PROPOSED FY14 ACTIVITIES

FY13 closes the first CRUSER Innovation Thread, continues work along the second and begins the third (*see Figure 82*). The following deliverables are planned:

- CRUSER plans to host a third event in the Robo-Ethics Continuing Education Series (RECES) presenting legal, social, cultural, and ethical issues for operators, acquisition professionals, and engineers in San Diego, California
- CRUSER will sponsor experimentation in FY13 of the most promising technologies from the May 2012 CRUSER Technical Continuum
- CRUSER will host a technical gathering for Thread 3 in April or May 2014 in conjunction with the annual unmanned systems research fair at NPS to explore concepts generated the September 2013 WIW
- CRUSER has planned to sponsor a technical exposition at ONR in Washington DC to share the results of the CRUSER Innovation Thread research and experimentation. This event is part of FY14 planning, however execution may require easing of the DoD travel restrictions
- CRUSER will continue to sponsor NPS faculty research and experiments across the holistic topic areas not traditionally sponsored by ONR technical funds such as human resources, human systems integration, concept exploration, and others. The FY14 call for proposals is in Appendix E of this report.
- CRUSER will provide a discussion venue for new Navy initiatives. For example, ongoing dialogue between the Naval Postgraduate School, the Naval Academy, and the Naval War College constituting the Navy Robotics Education Continuum will provide an opportunity for all three Navy schools to share their unmanned systems curricula to provide better alignment. CRUSER will also further explore an expanded relationship with the Naval Reserve Officers Training Corps (NROTC) Program
- CRUSER will sponsor a WIW in September 2014 to complete FY14, and begin CRUSER Innovation Thread 4.

- CRUSER will continue to fund NPS student travel to participate in research, experimentation, and wargames dealing with all aspects of unmanned systems
- CRUSER will continue to recruit community of interest members, produce monthly newsletters, and hold monthly community-wide meetings.
- CRUSER will continue to sponsor and participate in STEM outreach events relevant to robotics education, including NROTC support

B. LONG TERM PLANS

Projected to continue into FY14, CRUSER plans to catalog degree programs, short courses, and certificate programs nationwide. Integration of robotics and unmanned systems into educational programs in Naval academia such as USNA, NWC, in the NROTC, as well as in other U.S. military academic institutions. Long term plans include the creation of short course programs as identified by community of interest, and a continued effort to align curricula for interdisciplinary autonomous systems education on the NPS campus.

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APPENDIX A: SELECTED PUBLICATIONS AND TECHNICAL REPORTS

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 interest in CRUSER.

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/

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.

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.

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*.

Du Toit, N.E.; Burdick, J.W. (2012) "Robot Motion Planning in Dynamic, Uncertain Environments," *IEEE Transactions on Robotics,* Vol. 28, Issue 1, pp. 101-115, 2012.

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

Green, D. (2012). "ACOMMS Based Sensing, Tracking, and Telemetry," *Proc. 3rd WaterSide Security Conference*, Singapore, 28-30 May 2012

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.

Guest, Peter S., Trident Warrior 2013 (2013). “Demonstrating the use of unmanned aerial vehicles for characterizing the marine electromagnetic propagation environment,” presented at the *NPS CRSUER Monthly Meeting*, Naval Postgraduate School, Monterey CA, 11 September 2013.

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.

King, R. E. (2012). “Localization of a Mobile Node in an Underwater Acoustic Network,” *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012

Kline J. and L. Englehorn (2011). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Warfare Innovation Workshop (WIW) 2011 After Action Report*, released October 2011.

Kline J. and L. Englehorn (2012). *NWDC/ CRUSER Warfare Innovation Workshop (WIW) 2012 After Action Report: Advancing the Design of Undersea Warfare,* released November 2012.

Kline J. and L. Englehorn (2011). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Annual Report 2011: The Startup Year*, released December 2011.

Kline J. and L. Englehorn (2011). *Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) Annual Report 2012: The Transition Year*, released November 2012.

Kline, J. and L. Englehorn, *Maritime Defense and Security Research Program, Final Report, 2004-2011*, Naval Postgraduate School NPS-NSI-11-01, November 2011

Lin, K. Y., Atkinson, M. P., Chung, T. H., & Glazebrook, K. D. (2013). A Graph Patrol Problem with Random Attack Times. *Operations Research*, 61(3), 694–710.

Mahmood, A., M. Chitre, and M. Armand (2012). “Improving PSK performance in snapping shrimp noise with rotated constellations,” *Proc. WUWNet'12: 7th ACM International Conference on Underwater Networks & Systems*, Los Angeles, CA, pp. 1-8, November 2012

Muratore, M., Silvestrini, R. T., & Chung, T. H. (2012). Simulation Analysis of UAV and Ground Teams for Surveillance and Interdiction. *The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, OnlineFirst.

Otnes, R. and V. Forsmo, H. Buen (2012). *NGAS Sea Trials*, Gulf of Taranto, Italy, September 2011, January 2012

Otnes, R. (2012). “NILUS – An Underwater Acoustic Sensor Network Demonstrator System,” *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012

Otnes, R. and J. Rice (2013). “Underwater acoustic sensor networking in NGAS 2012 sea trial at Oslo Fjord, Norway,” *Proc. 1st Underwater Acoustics Conf*., Corfu, Greece, June 28, 2013

Rice, J. (2011). “Maritime Surveillance in the Intracoastal Waterway using Networked Underwater Acoustic Sensors integrated with a Regional Command Center,” invited presentation to *Small Vessel Security Threat Conference*, San Francisco CA, 29 September 2011

Rice, J. (2011). “Seaweb ASW Sensor Network,” FY11 year-end project report for publication in *ONR Ocean Battlespace Sensing*, December 2011

Rice, J. and G. Wilson, M. Barlett (2012). “Deep Seaweb 1.0 Maritime Surveillance Sensor Network,” *NDIA 2012 Joint Undersea Warfare Technology Spring Conference*, Undersea Sensors technical track, San Diego CA, 26-29 March 2012

Rice, J. (2012). “Node Ranging, Localization and Tracking as Functions of Underwater Acoustic Networks,” *Proc. Acoustics 2012* Hong Kong, p. 91, 13-18 May 2012

Rice, J. and C. Fletcher, B. Creber, B. Marn, S. Ramp, F. Bahr (2012). “Implementation of an Underwater Wireless Sensor Network in San Francisco Bay,” *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012

Rice, J. (2012). “Project MISSION – Maritime In Situ Sensing Inter-Operable Networks,” *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012

Rice, J. (2012). “Weaponized Underwater Surveillance Network,” *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012

Rice, J. and C. Fletcher, B. Creber, B. Marn, S. Ramp, F. Bahr (2012). “Implementation of an Underwater Wireless Sensor Network in San Francisco Bay,” *Proc. 3rd WaterSide Security Conference*, Singapore, 28-30 May 2012

Rice, J. (2012). “Seaweb Subsurface Sensor Network for Port Surveillance and Maritime Domain Awareness,” *NMIO Technical Bulletin*, National Maritime Intelligence-Integration Office, Summer 2012 issue, Vol. 3, pp. 10-14, August 2012

Rice, J. and M. Chitre (2013). “Maritime In Situ Sensing Inter-Operable Networks involving Acoustic Communications in the Singapore Strait,” *CRUSER Technical Continuum*, Monterey, CA, April 9, 2013

Rice, J. and M. Chitre (2013). “Maritime In Situ Sensing Inter-Operable Networks involving Acoustic Communications in the Singapore Strait,” *ONR Ocean Acoustics Review*, Bay St. Louis, MS, April 24, 2013

Rochholz, T. (2012). “Wave-Powered Unmanned Surface Vehicle Operation in the Open Ocean: A Station Keeping Asset for Distributed Netted Systems; PAC X: Transpacific Crossing of Wave Glider USVs,” *Proc. 10th International Mine Warfare Technology Symposium*, Monterey CA, 7-10 May 2012

Rochholz, T. (2012). “Wave-Powered Unmanned Surface Vehicle as a Station-Keeping Gateway Node for Undersea Distributed Networks,” presented at *NDIA Undersea Warfare Technology Conference*, Groton, CT, 24-27 September 2012

Rothal, J. and A. Davis (2011). *A Sampling of NPS Theses and Reports on UxS*, produced by the Dudley Knox Library, released August 2011.

Shankar, S. and M. Chitre (2013). “Tuning an underwater communication link,” *Proc. IEEE OCEANS Conf.,* Bergen, Norway, June 2013

Streenan, A. and Du Toit, N.E. (2013) “Diver Relative UUV Navigation for Joint Human-Robot Operations”, *MTS/IEEE Oceans Conference*, Sept. 23-26, San Diego, CA, 2013

Stevens, T., & Chung, T. H. (2013). Autonomous Search and Counter-Targeting using Levy Search Models. In *Proc. of 2013 IEEE Int’l. Conf. on Robotics and Automation*.

Yakimenko, O. A., & Chung, T. H. (2012). Extending Autonomy Capabilities for Unmanned Systems with CRUSER. *In Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences (ICAS 2012).* Brisbane, Australia.

Yang, J. H., Kapolka, M., & Chung, T. H. (2012). Autonomy balancing in a manned-unmanned teaming (MUT) swarm attack. In *2012 International Conference on Robot Intelligence Technology and Applications*. Gwangju, Korea.

Weiss, J.D. and Du Toit, N.E. (2013) “Real-Time Dynamic Model Learning and Adaptation for Underwater Vehicles”, *MTS/IEEE Oceans Conference*, Sept. 23-26, San Diego, CA, 2013

Xargay E., V. Dobrokhodov, I. Kaminer, A. Pascoal, N. Hovakimyan, and C. Cao (2011). “Time–Coordinated Path Following of Multiple Heterogeneous Vehicles over Time–Varying Networks,” invited paper for *IEEE Control Systems Magazine, Special Issue on UAVs and Controls*, 2011.

Xargay, E., N.Hovakimyan, V.N. Dobrokhodov, I.I. Kaminer, C. Cao, I.M. Gregory (2012). “L1 Adaptive Control in Flight”, chapter in a *book “Progress in Aeronautics and Astronautics Series”, AIAA*, 2012.

Xu, N., G. Cai, W. Kang, and B.M. Chen (2012). “Minimum-time trajectory planning for helicopter UAVs using dynamic optimization.” *IEEE International Conference on Systems, Man, and Cybernetics*, Seoul, South Korea, October 2012.

Yakimenko, O.A., and Chung, T.H., "Extending Autonomy Capabilities for Unmanned Systems with CRUSER," *Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences (ICAS 2012)*, Brisbane, Australia, 23-28 September 2012.

Zhang, Jiexin, Yang Liu, Mikhail Auguston, Jun Sun and Jin Song Dong (2012). "Using Monterey Phoenix to Formalize and Verify System Architectures", *19th Asia-Pacific Software Engineering Conference APSEC 2012*, Hong Kong 4 – 7 December 2012. http://www.comp.polyu.edu.hk/conference/APSEC2012/

APPENDIX B: SELECTED PRESENTATIONS FY13

This list of briefings is representative of those given by CRUSER leadership in the third program year. It is not meant to be inclusive, only give a sense of the depth and breadth of interest in CRUSER.

DATE (mo/yr)	AUDIENCE
October 2012	National Symposium for Sensor and Data Fusion, as part of the DOD conference called Military Sensing Symposia - "Future Concepts in Unmanned Systems at the Naval Postgraduate School."
November 2012	RDML Kuhlman, SUBGP9
	VADM Syring, MDA
	CAPT Steven Richter, USN (ret), JHU/APL's National Security Affairs
	CAPT San Pedro, Program Manager for PMW 770 at PEO C4I (Undersea Integration)
January 2013	RDML Kenneth PerryVice Commander, Naval Mine and Anti-Submarine Warfare Command
	General Charles H. Jacoby, Jr., USNORTHCOM
	Jeff Smith, Bluefin Robotics
February 2013	Phil Molnar, Monterey County Herald
	RADM Jan E. Tighe, NPS Interim President
March 2013	Mr. Robert Ekstrom, NAVAIR 4.1 S&T Lead for Fleet Experimentation
April 2013	RADM Leigher
May 2013	Jeff Frericks, Boeing Chief Systems Architect
June 2013	Mr. Monty Hoskinson, ST&T Action Officer, J814, USSTRATCOM

	and Dr. Mark Brown, ST&T Deputy Branch Chief, J814, USSTRATCOM
	Ms. Lisa Sanders, Director, Science and Technology for Special Operations Research, Development, & Acquisition Center (SORDAC S&T) from SOCOM
July 2013	RADM Harry Athanasopoulos, HN (ret)
	Sean O'Keefe and Dr Jean Botti, EADS
August 2013	Vice Admiral David H. Buss Commander, Naval Air Forces and Commander, Naval Air Force, U.S. Pacific Fleet
September 2013	RDML Scott Jerabek, Commander Navy Warfare Development Command (NWDC)

APPENDIX C: SELECTED THESES AND 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).

Thesis project title/subject:	NPS Student (s)	
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	LCDR Eric L. McMullen,	FY13

Formation Flight Performance In A Simulator Environment	USN and MAJ Brian Shane Grass, U.S. Army	
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 Singaporean Navy	FY12

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 Vertical Nodes	Maj Jose D. Menjivar, USMC	FY12
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

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APPENDIX D: COMMUNITY

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

USN and USMC Organizations:	COMPACFLT
	Marine Corps Combat Development Command, Operations Analysis Division (MCCDC)
	NAVAIR
	Naval Research Laboratory (NRL)
	NAVSEA
	Naval Special Warfare Command (NSW)
	Naval Surface Warfare Center (NSWC) Carderock
	Naval Surface Warfare Center (NSWC) Crane
	Naval War College (NWC)
	Naval Undersea Warfare Command (NUWC) Newport
	Navy Office of General Counsel
	Navy PEO Littoral and Mine Warfare (LMW), PMS 408
	Navy Reserves
	Navy Warfare Development Command (NWDC)
	Office of Naval Intelligence (ONI)
	Office of Naval Research (ONR)
	Office of Naval Research - Global (ONR-G)
	Space Systems Center, Pacific (SSC Pacific)
	U.S. Naval Academy (USNA)

Other Government Organizations & Institutes:	AFIAA, USAF
	Army Research Laboratory (ARL), USA
	COMCARSTRKGRU TWO
	COMPHIBRON EIGHT
	COMSUBDEVRON FIVE
	CSDS-12
	Defense Advanced Research Projects Agency (DARPA)
	Department of Energy
	HQ TRADOC
	I MEF
	Joint Ground Robotics Enterprise (JGRE OUSD)
	Joint Unmanned Aerial Systems - Center of Excellence
	Lawrence Livermore National Laboratory (LLNL)
	Marine Corp Warfighting Lab
	MCIOC
	National Aeronautics and Space Administration (NASA)
	National Oceanographic and Atmospheric Administration (NOAA)
	NAVSEA
	Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD(AT&L))
	OPNAV
	PEO C4I
	Robotic Systems Joint Project Office
	SOCAFRICA

	SSC Atlantic
	State of Wisconsin
	SUBFOR
	U.S. Air Force Academy, USAF
	U.S. Army Robotics Center of Excellence
	U.S. Army Unmanned Aerial Systems - Center of Excellence
	U.S. Army Tank-automotive and Armaments Command (TACOM)
	U.S. Army War College
	USFFC
	USMC Pentagon
	U.S. Military Academy (USMA)
	USS Chung-Hoon
	USSTRATCOM
Non-Government Organizations:	
	Autonomous Undersea Vehicle Applications Center (AUVAC)
	Institute for Religion and Peace
	Monterey Bay Aquarium Research Institute (MBARI)
International	UK National Oceanography Centre
	Agency for Defence Development (ADD)
	French Air Force Academy
	LIG Nex1, South Korea
Academia:	Netherlands Defence Academy (NLDA), Eindhoven University of Technology (TU/e), School of Innovation Sciences: Philosophy & Ethics, TNO and Delft University of Technology

	American University
	Arizona State University
	Auburn University
	California State University at Monterey Bay (CSUMB)
	Carnegie Mellon University
	Georgia Institute of Technology
	Case Western Reserve U
	CSULB HHS
	Drexel University
	Georgia Tech Research Institute (GTRI)
	Indiana State University
	The Johns Hopkins University Applied Physics Laboratory (JHU/APL)
	Kansas State University (KSU)
	Macquarie University
	Marine Advanced Technology Education (MATE)
	Massachusetts Institute of Technology (MIT)
	Memorial University of Newfoundland
	MIT Lincoln Laboratory
	New Mexico State University
	Northeastern University
	Northwestern University
	Penn State University Applied Physics Laboratory (PSU/APL)
	Rensselaer Polytechnic Institute
	SUNY Stony Brook

	University of Alaska
	University of Idaho
	University of Iowa
	University of Hawaii
	University of New Brunswick
	University of North Dakota
	University of Notre Dame
	University of Oklahoma
	University of South Florida
Industry:	Virginia Tech
	AAI Corporation
	Advanced Acoustics Concepts
	Aerojet
	Aerovironment
	Alidade, Inc.
	Alpha Research & Technology, Inc.
	Applied Physical Sciences Corp.
	Applied Research Associates, Inc.
	Aurora Flight Sciences
	AUVSI Foundation
	BAE Systems
	Battelle
	BBN Technologies
	Bell Helicopter Textron, Inc.

	Bluefin Robotics Corporation
	Boeing
	Booz Allen Hamilton
	Boston Engineering Corporation
	Charles River Analytics
	Charles Stark Draper Laboratory
	Comphydro, Inc.
	Compsim LLC
	Computer Systems Center, Inc. (CSCI)
	Comtech Solutions, LLC
	CS-Solutions, Inc.
	Daniel H. Wagner Associates
	David Ricker Group, LLC
	Desert Star Systems
	Draper Lab
	Duzuki
	Dynetics
	ELG, Inc.
	EQC, Inc.
	FIRST Robotics
	General Atomics
	General Dynamics Information Technology (GDIT)
	General Dynamics Electric Boat
	General Dynamics Land Systems

	Hydr0 Source, LLC
	Innovative Vessel Design
	Insitu
	Institute for Homeland Security Solutions
	iRobot
	Joint Venture Monterey Bay
	Lockheed Martin
	McKinsey & Co.
	Makani Power, Inc.
	Maritime Applied Physics Corp. (MAPC)
	MDA Corporation
	MITRE
	MRU Systems
	NAVPRO Consulting LLC
	Neptune Minerals
	NNS
	Northrop Grumman
	NWUAV Propulsion Systems
	Oceaneering Technologies
	Ocog, Inc.
	Orca Maritime, Inc.
	Odyssey Marine Exploration
	Physical Sciences, Inc.
	QinetiQ

	The Radar Revolution
	Raytheon
	RIX Industries
	Rockwell Collins, Inc.
	Rolls Royce
	SAGE Solutions Group, Inc.
	SAIC, Inc.
	Soliton Ocean Services, Inc.
	Sparton Defense and Security
	Spatial and Spectral Research
	Spiral Technology, Inc.
	SRI International
	ST Aerospace
	Strategic Defense Solutions, LLC
	Systems Planning & Analysis, Inc.
	Tactical Air Support, Inc.
	TASC
	Tech Associates, LLC
	Teledyne RDI
	United Technologies Research Center (UTRC)
	Unmanned Vehicle Systems Consulting, LLC
	Vehicle Control Technologies, Inc.
Other:	Monterey County Herald
	The Salinas Californian

APPENDIX E: CRUSER FY13 CALL FOR PROPOSALS

From Technical to Ethical…..From Concept Generation to Experimentation…
http://CRUSER.nps.edu

<u>CRUSER Call for Proposals FY13</u>

PROPOSALS DUE DATE:	**10 Aug 12**
Selection Date:	**10 Sept 12**
Funding Period:	**31 Oct 12 – 30 Sept 13**
Funding Levels:	**$75,000 - $125,000** *(no indirect)*

<u>Research Goal:</u> 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 across the Navy and Marine Corps. The establishment of 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.

At the direction of the Secretary of the Navy, the Naval Postgraduate School leverages its long-standing experience and expertise in the research and education of robotics and unmanned systems to support the Navy's mission. The establishment of CRUSER serves as a vehicle by which to align currently disparate research efforts and integrate academic courses across discipline boundaries.

CRUSER will be 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 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 will host classified and unclassified websites and establish networking and collaborative environments for the community. Furthermore, with the operational needs of the Navy and the Marine Corps at its core, CRUSER will 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 and highlighting the educational mission of the Naval Postgraduate School.

Specific CRUSER goals are to:

- Provide a source for unmanned systems employment concepts for operations and technical research;
- Provide an experimentation program to evaluate 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 will take 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. Manning requirements, human systems integration, information processing, information display, training, logistics, acquisition, development, C2 architectures, legal constraints, levels of autonomy versus mission risk are just a sample of topics for research in addition to technical research areas for these systems.

<u>Funding</u>: Funding is not yet received for FY13; however the purpose of this call for proposals is to prepare researchers on campus to begin work as soon as possible in the fall of the new fiscal year. *CRUSER research funding should be considered a "seed" funding for one year, to more fully develop a research program to compete for regular ONR funding.* New research is the goal. The anticipated funding level is $3M dollars in FY13 with a proposed budget break down as follows:

Labor and Travel for Coordination Group:	$318K
Travel (Student research support and faculty):	$100K
Field Experimentation	$500K
Technical Symposium	$75K
Technical Fair at ONR for research travel	$40K
Education Advancement and Development	$167K
Faculty Research and Development	$740K
Social, Cultural, and Ethical Continued Education Symposium	$85K
ONR/NPS Seaweb Experiment in Singapore:	$252K
Equipment	$75K
STEM Events	$41K
Contracts and Conference Fees	$20K
Indirect (30.6% - FY12 amount)	$588K
Total	**$3000K**

About $700,000 dollars are anticipated to be available in FY13 for open research proposals, including participation in the CRUSER field experimentation. In

addition, student travel and support is also budgeted, so proposals should include anticipated student travel funding requirements, <u>but not include that amount in the total requested.</u>

Faculty members who receive CRUSER Research and Experimentation funds are expected to be fully active in supporting CRUSER's goals to include: monthly meeting attendance, presentations, CRUSER News articles, displays at Robots in the Roses, and participation at other CRUSER sponsored events, including presentations to ONR during the ONR CRUSER visit.

<u>Proposal Criteria</u>: Proposals will be evaluated on the following criteria:

1.) Student involvment
2.) Interdisciplinary, interagency, and partnerships with naval labs
3.) Partnerships with other sponsors' funding
4.) Research related to unmanned systems' catagories:
    a. Technical: Power, Sensors, Controls, Communications, Architectures, Human Factors, Information Processing and Dissemination
    b. Organization and Employment: Human Capital Requirements, Risk Analysis, Force Transition, Acquistion, Policy, Concept Generation evaluation and Authorities
    c. Social, Cultural, Political, Ethical and Legal
    d. Experimentation
    e. Defense against threat UxS capabilities
5.) New research area (Seed money to attract other contributors)
6.) Related to CRUSER mission thread: UxS support to naval operations
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. Hence proposals are expected to range from $75K - $125K

<u>Review and Selection Board</u>: Proposals will be evaluated by a panel of reviewers chaired by the Dean of Research and composed of the NPS CRUSER Advisory Board and CRUSER Director. Any member of the CRUSER coordination group or Advisory Board submitting a funding proposal will not serve on the panel.

<u>Proposed Format</u>: Short (3-6 page) proposals are solicited using the NPS research proposal format. The proposal should use NPS' research proposal front page and be clearly marked as "CRUSER Proposal FY13". Address and send to Director, CRUSER Jeff Kline at jekline@nps.edu and Lisa Trawick at cruser@nps.edu.

The following sections are nominally required:

1. Name of PIs, NPS Address, e-mail address, ID any security holders clearance
2. Period of Performance, Total Funding required, Student funding required (with names if available)
3. Description of the Project
4. Potential FY14 follow on efforts and potential or anticipated external funding
5. FY13 Budget Details
6. Self evaluation of proposal criteria above

APPENDIX F: CRUSER MANAGEMENT TEAM

DIRECTOR: Dr. Raymond Buettner 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 $3 million dollars a year, including the TNT, RELIEF, and JIFX projects. http://faculty.nps.edu/rrbuettn/about.html

DEPUTY DIRECTOR: Dr. Timothy H. Chung is an Assistant Professor of Systems Engineering at the Naval Postgraduate School. His research interests include probabilistic search optimization, degrees of autonomy for robotic systems, and multi-agent coordination for information gathering applications. His efforts lie at the interface between operations and robotics research. Professor Chung received his doctorate (2007) and M.S. (2002) at the California Institute of Technology in mechanical engineering, specializing in algorithms for distributed sensing and decision-making methods for multi-robot systems. He joined the NPS OR department in 2008 and currently holds a SECRET security clearance. http://faculty.nps.edu/thchung/

DIRECTOR OF STRATEGIC COMMUNICATIONS: Steve Iatrou is a Senior Lecturer in the Information Sciences Department at the Naval Postgraduate School. He is currently the Associate Chair of Distributed Learning, Academic Associate. He received a masters in Systems Technology from the Naval Postgraduate School (1992) and a Bachelors in Journalism and Mass Communication from the University of Oklahoma (1985).

DIRECTOR OF OPERATIONS: Ms. Lisa Trawick has been in the Air Force Reserves for 21 years and is currently serving as a Logistical Readiness Officer for the Surface Deployment and Distribution Command (SDDC). Her previous assignment was a full-time tour for 3.5 years at DFAS Internal Review (IR) as a Financial Data Analyst, where she won the DFAS IR Innovation Award in 2008. In her civilian life she spent 12 years at Frito Lay with various roles in manufacturing/warehouse operations and as a Demand Planner. She received a Bachelors in Statistical Computing from the University of Utah (1998) and a Masters in Information Technology from the Naval Postgraduate School (2008). Trawick holds a SECRET Clearance.

DIRECTOR OF CONCEPT GENERATION: Ms. 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 Multimodal Information Sharing Team (MIST), the Operations Research Department, and the NPS Graduate Writing Center. Other work at NPS has included curriculum development and instruction for an International Maritime Security course sequence. Ms. Englehorn holds a SECRET clearance.

DIRECTOR EMERTIUS/SENIOR ADVISORY COMMITTEE MEMBER: Mr. Jeffrey 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. Kline holds a TS/SCI clearance. http://faculty.nps.edu/jekline/

DIRECTOR OF CONCEPT GENERATION AND INNOVATION EMERITUS: Ms. Carol O'Neal, CAPT, USN (Ret.), is a Research Associate in the Operations Research Department at the Naval Postgraduate School, where she is supporting applied analytical research in optimization-based decision support tools for use in mission planning in the Globally Networked Maritime Headquarters with Maritime Operations Centers, and Warfare Concept Generation workshops. She has 30 years of extensive naval experience including command and major command tours in Navy recruiting and as a USNA Battalion Officer and NPS Dean of Students in Navy education. She graduated as the President's Honor Graduate from the Naval War College with a Masters in National Security and Strategic Studies and a Masters in International Relations from Salve Regina College. She was also selected for a Federal Executive Fellowship at RAND and a SEMINAR XXI fellow at MIT. O'Neal holds a SECRET clearance.

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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 FY13 annual report summarizes CRUSER activities in its third year of operation, and highlights future plans.

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

POC: Dr. Raymond Buettner, CRUSER Director
http://cruser.nps.edu
cruser@nps.edu

LIST OF ACRONYMS AND ABBREVIATIONS

A2AD	anti-access area denial (*A2/AD also used*)
ACTUV	ASW continuous trail unmanned vessel
AREPS	Advanced Refraction Effects System
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
CANSOF	Canadian Special Operations Forces
CAVR	NPS Center for Autonomous Vehicle Research
CENETIX	Center for Network Innovation and Experimentation
CNO	Chief of Naval Operations
COAMPS	*U.S. Navy's mesoscale numerical forecast model*
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
DoD	Department of Defense
DON	Department of the Navy
DRDC	Defence R&D Canada
EMCON	Emissions controlled
FFI	Norway Defence Research Establishment
FIU	Florida International University
FWG	Germany Federal Armed Forces Underwater Acoustic and Marine Geophysics Research Institute
GCS	Ground control station
HERO	Hazards of electromagnetic radiation to ordnance
IRND	improvised radiological or nuclear device
ISR	Intelligence, surveillance, and reconnaissance
JCA	Joint campaign analysis
JIFX	Joint Interagency Field Exploration
LAR	lethal autonomous robot

LDUUV	large displacement UUV
LiPo	Lithium Polymer
MATE	Marine Advanced Technology Education
MBARI	Monterey Bay Aquarium Research Institute
MDA	Maritime domain awareness
METOC	Meteorological and oceanographic
MILDEC	Military deception
MINDEF	Singapore Ministry of Defense
MIO	Maritime threat detection and interdiction operations
MISSION	Maritime In Situ Sensing Inter-Operable Network
MPPT	Maximum peak power tracker
MvM	Many versus Many
NAVAIR	U.S. Naval Air Systems Command
NAVO	U.S. Naval Oceanographic Office
NAVSEA	U.S. Naval Sea Systems Command
NORSOF	Norwegian Special Operations Forces
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NUS	National University of Singapore
NUS ARL	National University of Singapore Acoustic Research Laboratory
NUWC	Naval Undersea Warfare Command
NWC	Naval War College
NWDC	Navy Warfare Development Command
ONR	Office of Naval Research
OR	Operations Research Department, NPS
OSD	Optimal spectral decomposition
QR	Quick Response (*QR code*)
RECES	Robo-Ethics Continuing Education Series
RF	radiofrequency
RLS	recursive least square
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
SQMD	squadron manpower documents
SSC Pacific	U.S. Space & Naval Warfare Systems Center
SSG	Strategic Studies Group
STEM	Science, technology, engineering, and mathematics
TaLEUAS	Tactical Long Endurance Unmanned Air System
TDA	Tactical decision aid
TechCon	CRUSER Technical Continuum
TERN	Tactically Exploited Return Node
THAUS	Tethered hovering autonomous underwater system
TNT	Tactical Network Testbed
TRANSEC	Transmissions security
TUAV	Tactical unmanned aerial vehicle
UAS	Unmanned aerial system
UAV	Unmanned aerial vehicle
UBS	Unmanned buoy system
UCLASS	Unmanned Carrier Launched Airborne Surveillance and Strike aircraft
UCSC	University of California at Santa Cruz
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
WIW	Warfare Innovation Workshop

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ACKNOWLEDGMENTS

CRUSER thanks the entire community of interest who joined us since the program inception in March 2011 – we look forward to many successful years to come.

CRUSER owes its program success to the extraordinary work of the first CRUSER Director, CAPT Jeff Kline, USN (ret.)

CRUSER appreciates the support and guidance of former Under Secretary of the Navy Robert Work, and we wish him luck in his future efforts.