Consortium for Robotics & Unmanned Systems Education & Research (CRUSER)

PI: CAPT Jeff Kline, USN (ret.)
Naval Postgraduate School
Monterey CA 93943
phone: (831) 656-7946 fax: (831) 656-2595 email: jekline@nps.edu

Award Number: N0001412WX20510
http://cruser.nps.edu

LONG-TERM GOALS

At the direction of the Secretary of the Navy (SECNAV), the Naval Postgraduate School (NPS) leverages its long-standing experience and expertise in the research and education of robotics and unmanned systems (UxS) to support the Navy's mission. The Consortium for Robotics and Unmanned Systems Education and Research (CRUSER) program grew out of the SECNAV's UxS prioritization, and concurrent alignment of UxS 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.

Top level 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 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.

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, 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 will inform and augment traditional technical research in unmanned systems and aid in their integration into fleet operations.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2012**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Consortium for Robotics & Unmanned Systems Education & Research (CRUSER)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School Monterey CA 93943**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVES

From Technical to Ethical… From Concept Generation to Experimentation…
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 intends to encompass the successful research, education, and experimentation efforts in unmanned systems (UxS) currently ongoing at NPS and across the naval enterprise. Controls, sensors, design, architectures, human capital resource requirements, concept generation, risk analysis and field experimentation are just a few interest points.

Major aligned events starting in FY11 through FY13 include concept generation workshops, technical symposia, and field experimentation to test selected technologies. However, research and education will include a broader landscape than just mission areas.

APPROACH

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, will lead CRUSER and execute the collaborative vision for the Consortium. The Director will encourage, engage, and enhance 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 welcome to contribute and participate.

WORK COMPLETED

FY12 is CRUSER's first full year in operation, and as a transition year continued many items started in FY11 such as the Community of Interest database – which is over 800 members near the close of FY12, a monthly newsletter, monthly VTC meetings, and online presence to include a SIPR site. Community-wide monthly meetings are held on the Naval Postgraduate School campus in Monterey, and CoI members are encouraged to attend by phone or via VTC to allow for collaboration with those are not located at NPS. CRUSER sponsored a Warfare Innovation Workshop (WIW) at the close of FY11 focusing on revolutionary concept generation using evolving Naval Unmanned Systems technologies with three teams of NPS students and young engineers from Navy labs and industry, along with a team with more experienced NPS faculty and engineers from Navy labs and industry. Five selected focus areas from the concepts generated during the September 2011 WIW provided the basis for presentations that refined those concepts at the CRUSER Technical Continuum held May 2012 in coordination with the Tenth International Mine Warfare Technical Symposium in Monterey, California. It is anticipated that at least three of the presentations will lead to field experimentation in FY13.

Seed funding was provided to eight NPS faculty members to start research across many aspects of unmanned systems, to include the joint ONR/NPS Seaweb at-sea experimentation program with Singapore. CRUSER has also funded NPS student travel to participate in research, experimentation, and war games 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. For example, hosting initial discussions for the Navy's Robotics Education Continuum in conjunction with the CRUSER Technical Continuum provided an opportunity to align unmanned systems education at USNA, NPS and NWC. Additionally, in January 2012 CRUSER hosted a legal, social, cultural, and ethical continuing education symposium for operators, acquisition professionals, and engineers in the Washington D.C. area in coordination with OPNAV N2/6 and ONR. Building on the success of this educational symposium, a similar event is being planned for FY13 in San Diego.

RESULTS

1) Maritime In Situ Sensing Inter-Operable Network (MISSION)
POC: Professor Joe Rice (jarice@nps.edu)

Persistent maritime surveillance is a challenging problem that requires the deployment of autonomous underwater sensor networks. The Seaweb Maritime In Situ Sensing Inter-Operable Network (MISSION) project will develop and test national through-water acoustic communications and networking capability with emphasis on operations in noisy environments and cross-nation interoperability. A bilateral Research Development Test and Evaluation (RDT&E) project that involves collaboration by the U.S. and Singapore in advancing state-of-the-art, through-water acoustic communications and networking technology, the MISSION project has conducted several field experiments in FY12.

This is a multiyear project, starting with initial planning in FY11. FY12 is the start of year one. Anticipated completion is at the start of FY14 with final sea trials in October 2013 and results published in December 2013. A more detailed timeline is available.

2) Passive UxV Navigation using Visual Sensors
POCs: Dr. Roberto Cristi (rcristi@nps.edu) and Dr. Oleg Yakimenko (oayakime@nps.edu)

The overall goal of this research is to design a novel capability enabling unmanned vehicles to navigate with respect to a stationary or moving target with unknown position using passive inertial sensors (IMU and GPS) and mono vision (EO or IR). That includes estimating a relative position of an aerial platform intended to land autonomously onto a moving platform with no help provided by/from this platform. The research includes both theoretical study and practical implementation where the developed algorithms are to be implemented on an aerial payload delivery platform, ultra-light weight unpowered guided parafoil system, deployed from an unmanned aerial vehicle to land onto a ship's deck.

In the proposed approach, using standard concepts from 3D vision we reformulated the problem as a linear estimation with two distinct dynamic models, one for in-frame events (when the target is in the camera's field of view) and one for out of frame events (when the target is not in the camera's field of view). While the in frame model is fairly standard, the out-of-frame model is based on epipolar geometry by which the last observation (before losing the target) and the first observation (right after we acquire it again) can be viewed as a pair of stereo observations of the same target with unknown displacement. Camera observations together with its position and orientation can then be related to the unknown target out of frame displacement to yield the necessary observation for the dynamic model. Standard recursive optimal filtering (like Kalman filtering) can then be used to recursively track the target.

The particular feature of the developed approach is that the nonlinearities are "memoryless". In this way, the dynamic model is linear, thus guaranteeing the convergence of the estimator. However the drawback is that the nonlinear processing of the observations causes the measurement errors to be nongaussian, biased and also sensitive to the geometry of the system. More recent techniques based on the Unscented Kalman Filter were also investigated to provide the more reliable estimates in the presence of sensor errors.

The project involved extensive theoretical and trade-off studies based on both simulated and experimental data and included participation of several master students and one PhD student. Actual implementation and integration with onboard guidance algorithm is expected to involve students and instructors of the U.S. Naval Academy who built their version of Snowflake and have seamanship training craft of the "YP 676" class equipped with and aft deck for autonomous landing trials.

3) Tropical Cyclone Reconnaissance

POC: Dr. Patrick Harr (paharr@nps.edu)

Tropical cyclones (TCs) form and initially track over data sparse, oceanic regions. Forecasts of tropical cyclone structure and wind radii, as well as formation, intensification, and motion are based upon guidance from numerical weather prediction models. These models integrate the basic equations that govern atmosphere-ocean dynamic and thermodynamic properties as an initial-value problem. Therefore, the accuracy of the simulation (i.e., numerically-generated forecast) is dependent upon the quality of the initial conditions used to initialize the time integration. Because of the lack of in situ data in the region of a tropical cyclone, the initial conditions are often based upon a blend of a previously-generated, short-term (i.e., 6 h) model forecast and synthetic observations that are based on an assumed storm structure for a given intensity. Other sources of information for wind radii estimation and model initialization are data derived from remotely-sensed, satellite-based observations. However, crucial satellite observations of surface wind radii such as from a satellite-based scatterometer are no longer available due to satellite failure and lack of a replacement. Further, the uncertainty in satellite-based observations can be large, which lowers the influence of these observations in the definition of initial wind radii as well as initial environmental and tropical cyclone inner core conditions for numerical model integrations.

Over the North Atlantic Ocean, an operational manned aircraft-based TC reconnaissance program is conducted by the United States Air Force. However, no such program is conducted over the western North Pacific (WPAC), where the maximum annual number of TCs occur. Rather, remotely-sensed observations from satellites provide data on TC characteristics. While operational forecasts of TC track over the WPAC have improved, the rate of improvement has declined, and no such decline has been observed over the North Atlantic. In this study, the declining rate of improvement in WPAC forecast accuracy is examined relative to the lack of direct observations.

The capabilities of manned-aircraft are compared with use of a Global Hawk unmanned aerial system for use as an observing platform. This is proposed in view of a declining capability in satellite data coverage. Current Global Hawk programs are reviewed with respect to requirements for operational tropical cyclone reconnaissance over the western North Pacific. A multi-year demonstration project is proposed to obtain in situ observations of TC location and intensity. The observation impacts on improved tropical cyclone forecasts will be assessed such that a positive impact will lead to recommendation of a Global Hawk for operational tropical cyclone reconnaissance.

4) Joint Optimization of UUV Sensing and Sampling

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

This project was jointly funded by the CRUSER and the Naval Oceanographic Office (NAVO) in FY12. Five NPS METOC/USW students have been working on the project for their MS degrees with the participation of scientists as co-advisors with inter-disciplinary backgrounds from multi-institutions: Peter Chu (Oceanography, NPS), Timothy Chung (Systems Engineering, NPS), Thomas Wettergren (Applied Mathematics, NUWC-NP), Ronald Bestch (Mine Warfare, NAVO), Frank Bub (Ocean Modeling and Prediction, NAVO), and Peter Fleischer (Sedimentology, NAVO). Five theses have been completed. Most of them will be published in scientific journals and presented in national and international conferences. Five NPS theses have been produced from this project:

1) LT Kristie Colpo, *Joint Sensing/Sampling Optimization for Surface Drifting Mine Detection with High-resolution Drift Model*, MS, METOC, September 2012.
2) LCDR Timothy Knapp, *Ocean Resurvey-Tactical Decision Aid With Joint Optimization of Sampling and Sensing, MS*, METOC, September 2012.
3) LCDR Joses Yau, *Localization of Surface or Near-surface Drifting Mines for Unmanned Systems in the Persian Gulf*, MS, Physical Oceanography, March 2012
4) LCDR Jason Gipson, *Application of Mine Burial Expert System to Mine Warfare Doctrine*, MS METOC, June 2012
5) LT Patrick Earls, *New Bottom Roughness Calculation from Multibeam Echo Sounders for Mine Warfare*, MS, Physical Oceanography, September 2012

The Navy's ocean models were taken as an important component into optimal UUV sensing and sampling with application to mine warfare (MIW) and anti-submarine warfare (ASW). Two high-resolution NAVO operational ocean models, the Navy Coastal Ocean Model (NCOM) and Delft3D, are used for the study. Frank Bub at NAVO conducted thorough quality control on these models and provided near real-time ocean environmental data for the Persian Gulf (*see Figure 1a*) and Hampton Roads Inlet (*see Figure 1b*) with the horizontal resolution up to 60 m and time increment of 10 min.

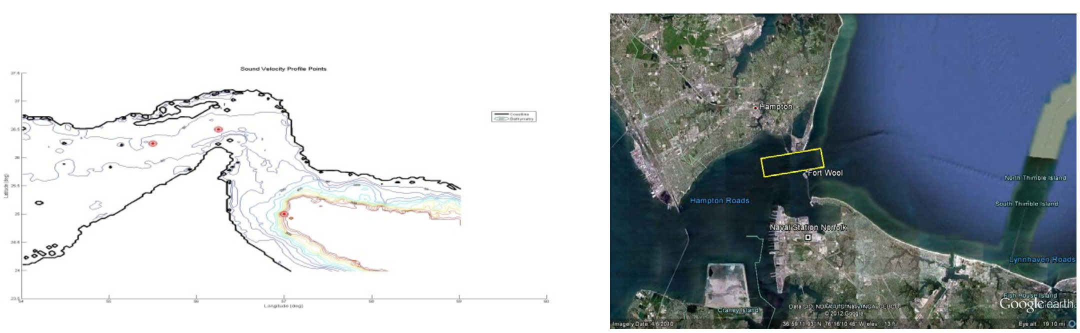

Figure 1: Navy's ocean models for (a) Persian Gulf, and (b) Hampton Roads inlet

This project improves time-varying search areas, tactical sensor network, ocean resurvey tactical decision aid, and mine warfare doctrine with ocean models and data. The search and detection problem formulation with near real-time environment, extensive simulation studies, and subsequent statistical analysis provide insights into how to incorporate real-time and/or historical oceanographic data to maximize the probability of detection.

Navy tactical ocean environmental models and data are very important and useful for the CRUSER program. Tasks accomplished in FY12 to effectively incorporate the ocean models in the UUV operations within this project are included in five individually titled subprojects, each the subject of an NPS student thesis. The first, *Joint Sensing/Sampling Optimization Algorithm for Mine Detection Using UUV* included work by Peter Chu, Kristie Colpo, Thomas Wettergren, Frank Bub (NAVO), and Ronald Betsch. By incorporating tactical oceanographic models into optimal sensing/sampling network, an algorithm has been developed to determine the location and time with minimal number of UUV deployments to have high detection probability (*see Figure 2*) for moving targets (such as drifting mines and maritime IEDs). Besides, a mine drift model was also developed on the base of ocean circulation model. It offers an estimation of surrounding environmental effects and therefore provides time critical estimations of target movement. These approximations can be used to further optimize sensor network components and locations through a defined methodology using estimated detection probabilities.

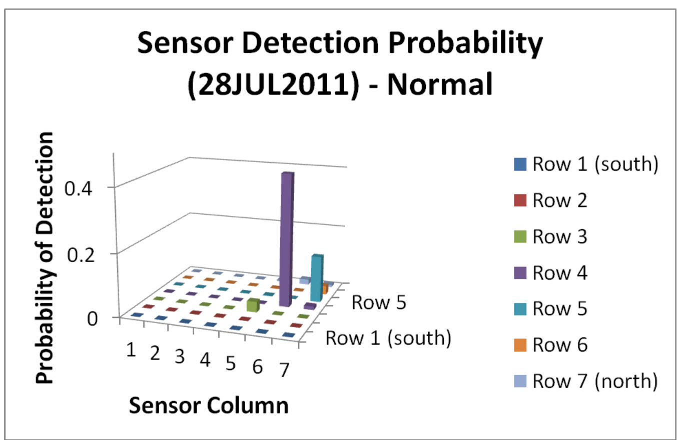

Figure 2. Calculated sensor detection probability by the joint optimization algorithm with the Navy ocean model for the Hampton Roads inlet on 28 July 2011

The second set of work, *Ocean Resurvey-Tactical Decision Aid with Joint Optimization of Sampling and Sensing*, was conducted by Peter Chu, Timothy Knapp, and Ronald Betsch. The combination of temperature and salinity variation has a significant effect on the sound velocity profile of the ocean. Many militarily significant ocean areas exhibit rapid change in ocean temperature and salinity, making operational monitoring critical to maintain our military advantage and presenting an operational challenge for military planners on how to efficiently schedule ocean survey assets so as to optimize the survey area. The Ocean Resurvey-Tactical Decision Aid (OR-TDA) was developed as a supplemental tool to the Navy Coastal Ocean Model (NCOM) that will aid military planners in scheduling limited survey assets in areas of the world that are of military significance. The OR-TDA is intended to be a decision aid to help optimize the time and location to deploy ocean sensors in order to get realistic sound speed profiles for accurate estimation of the acoustic transmission for naval operations. Using

NCOM output data, the OR-TDA will help planners by identifying areas of the ocean that are changing more rapidly than others (*see Figure 3*). Planners can then use that information to help prioritize ocean locations to be re-surveyed and then schedule survey assets appropriately.

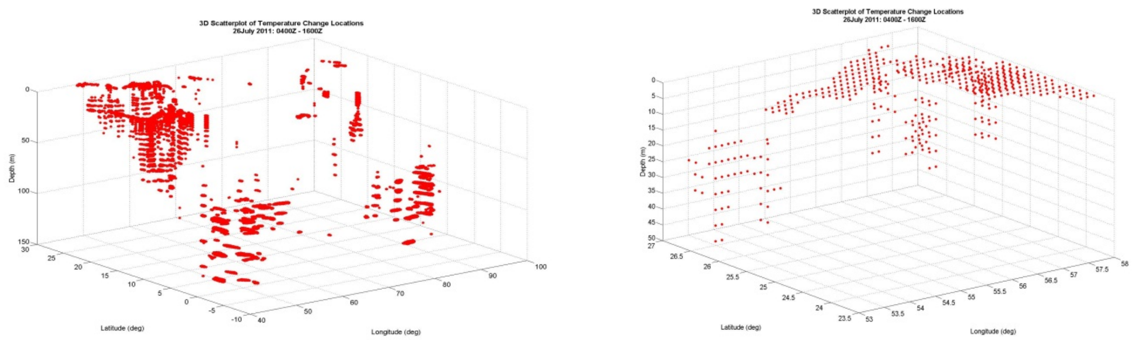

Figure 3. OR-TDA sample output plots in the Persian Gulf: (a) temperature, and (b) salinity

Development of Integrated Search and Ocean Model for Detecting Drifting Mines with Unmanned Systems in the Persian Gulf, a thesis by Joses Yau, involved the work of Dr. Timothy Chung, Peter Chu, and Ronald Betsch. Enhanced search effectiveness is facilitated by the use of robotic search agents, such as a tactical unmanned underwater vehicle (UUV) or unmanned aerial vehicle (UAV), leveraging simulation methods to inform the search process. The presented work investigates the impact of using naive versus optimized search patterns on localizing a drifting object, including a surrogate ocean model using idealized flow as well as historical data sets with Weibull-distributed perturbations. Numerical studies and extensive analysis using different permutations of model parameters (including the relative speed of the drifting object, time late in the searcher's arrival to the search area, sensor sweep width, and duration of the search mission) identify the significant factors affecting the overall probability of detection (*see Figure 4*). Such insights enable further explorations using empirical datasets for specific oceanographic regions of interest.

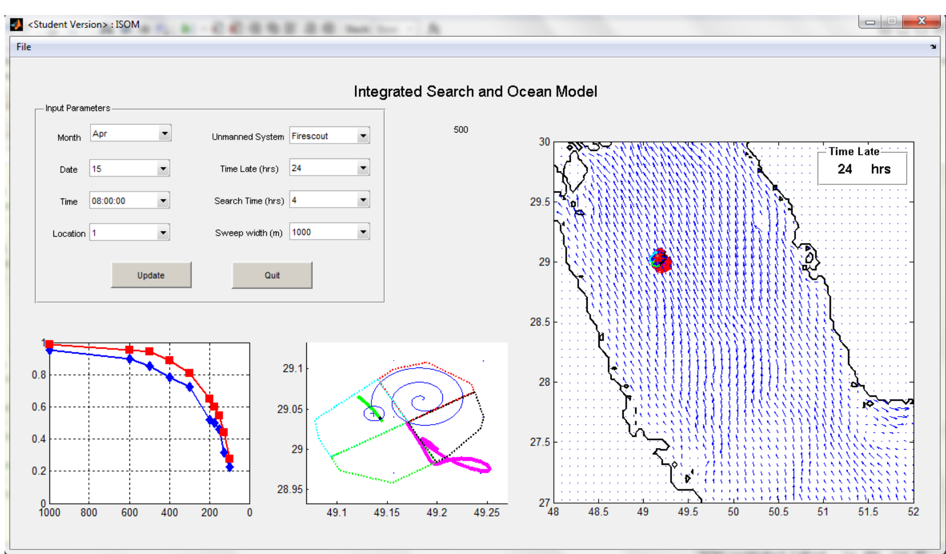

Figure 4. Integrated search and ocean model for detecting surface drift mines

New Bottom Roughness Calculation from Multibeam Echo Sounders for Mine Warfare was a project conducted by Peter Chu, Patrick Earls, and Ronald Betsch. Bottom roughness has a significant effect on acoustic backscattering on the ocean bottom. Sonar systems rely on backscattering and shadows for detecting objects lying on the seafloor. The seafloor is rather complex including craters, gullies, seaweed, rocks, sand ridges, tall obstructions, deep holes and sloping regions. Underwater mines can be hidden around these objects to make it more difficult to be detected. High resolution (1 m × 1 m) seafloor data collected by the Navy using multibeam echo sounder (EM710) off the western coast of Saipan was processed by the MB Systems. The advanced least-square method is used to establish new bottom reference level from the EM710 data. After removing the reference level, the high-resolution bathymetry data converts into bottom roughness percentage using a threshold. The calculated bottom roughness percentage is ready to be incorporated into the current Navy doctrine. Two new (gradient and mathematical morphology) methods have been developed in this thesis to calculate the bottom roughness without the reference level (*see Figure 5*). Statistical analysis was conducted to illustrate the added value of the new bottom roughness calculation.

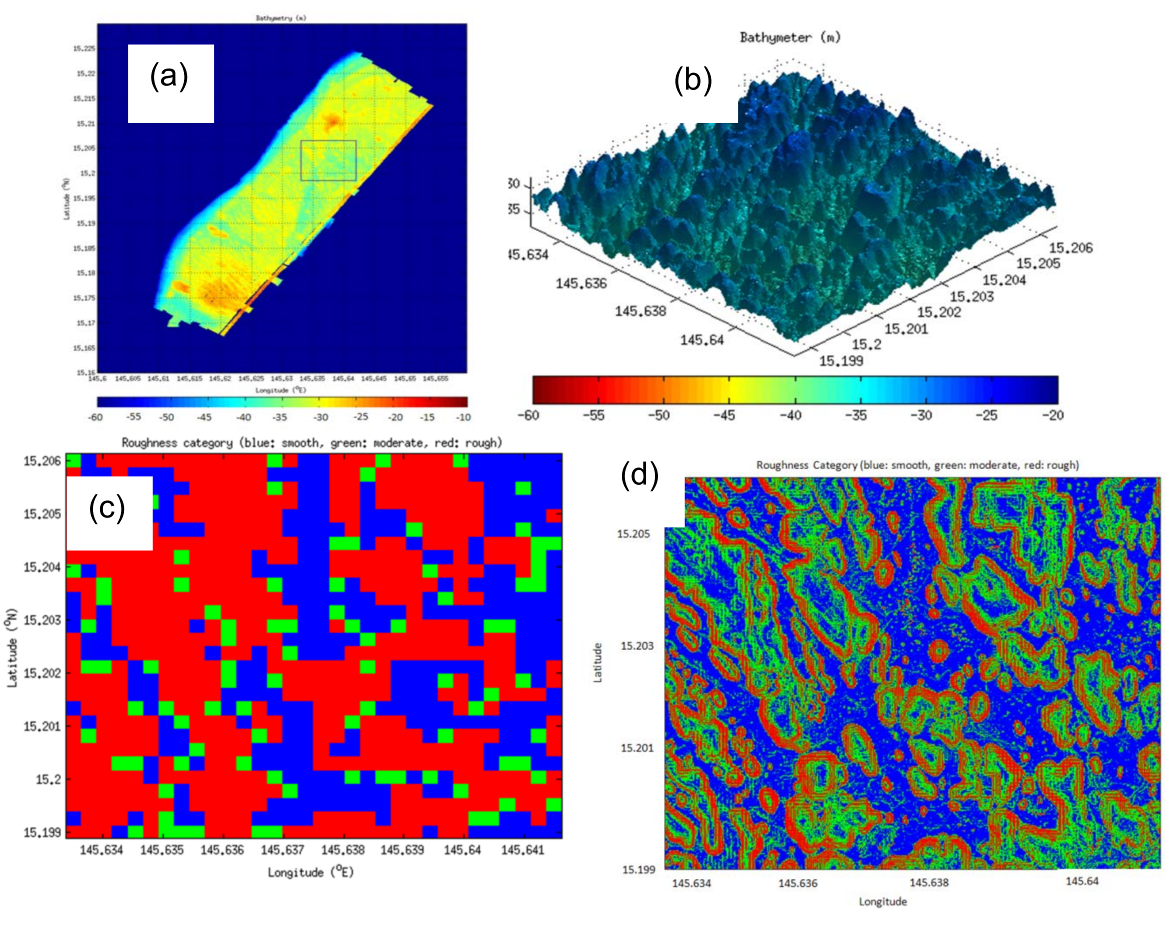

Figure 5. Bottom roughness from multibeam echo sounders (EM710): (a) experimental area, (b) bottom bathymetry from EM710, (c) bottom roughness with the conversion of bathymetry into roughness percentage, and (d) new gradient method for bottom roughness

Finally, *Application of Mine Burial Expert System to Mine Warfare with UUV* resulted in a thesis by Jason Gipson with supporting work by Peter Chu, and Peter Fleischer. An assumption central to this project work is that sea mines are the quintessential asymmetric threat to the Navy's ability to conduct operations in the maritime domain. Presently, the U.S. Navy has a limited ability to find buried mines. This capability gap is compounded by the apparent phase lag between emergent technology and the existent outdated Mine Warfare (MW) doctrine used to for planning and measuring clearance success; where such elements like the use of the doctrinal bottoms types can skew a commander's decision–making process for how to properly apply technology to defeat the threat.

Understanding the extent of sea mine burial is pivotal for executing MCM clearance operations effectively. The Mine Burial Expert System (MBES) was developed to determine the dynamic physical behavior for and magnitude of sea mine burial while communicating the inherent uncertainty in the specified degree of burial. This thesis showed the utility of the MBES to make accurate burial predictions utilizing Bayesian networks, deterministic models for burial, mine threat and environmental uncertainty (e.g. sediments) and expert opinion in comparison to traditional "limited" doctrinal methods; especially in terms of resolution. It further expounds on the current operational state of the MBES—highlighting the need to leverage emergent technologies and relationships between the scientific, acquisition and warfighter communities especially use of UUVs.

5) Roadmap for Reduction of Total Ownership Cost (TOC)
POC: Dr. Dan Nussbaum (danussba@nps.edu)

According to the methodology section of our proposal, we planned to research 4D/RCS and Technomics to accomplish our objectives. We analyzed the implications of using 4D/RCS as a common architecture for all UAVs, and drafted a white paper on this topic. We have also researched a paradigm shift in UAV cost estimation, which will take the form of a student thesis by LT K. Beth Jasper. LT Jasper will finish her write up by the end of September 2012. Instead of focusing on Technomics, however, we decided to look at whether the use of an Open Architecture model for unmanned systems resulted in cost savings. LCDR Paula Firenze completed a thesis on this subject in June 2012.

This project was addressed in three parts, the first being the 4D/Real-time Control System (4D/RCS). The trend of increasing drone missions, with respect to missions for manned aircraft, shows that drone missions may be the way of the future. As such, the O&S costs of UAVs must be optimized. The 4D/RCS architecture is a hierarchical control structure that addresses the problems faced by an intelligent vehicle system, such as a UAV, to accomplish mission goals. In 4D/RCS, the lowest cost plan is always implemented. There are a number of cost functions at each level within the architecture to determine the planned action at that particular level.

For example, the 4D/RCS architecture should use the fewest number of UAVs to accomplish a particular mission. This saves on fuel costs because fewer UAVs would be travelling to the target location. By optimizing UAVs with regards to the missions performed, there will also be an increase in life cycle for the UAVs in the squadron and fewer wasted man-hours because the UAVs will need fewer repairs within a given time period.

The next section of this three part project in FY12 took a closer look at a paradigm shift in UAV cost estimation. The purpose in this part of the project is to provide a TOC that reflects the end-to-end costs associated with ISR platforms. We do this by developing an amended, and expanded, Work

Breakdown Structure (WBS) within the standard cost estimating methodology. Additional WBS elements include: C2 function, data uplink, bandwidth, intelligence manning, data storage, software licensing, exploitation hardware, processing hardware, and ground support elements.
Research questions that addressed through this approach were:

- *What are the total costs associated with manned and unmanned aerial vehicles from exploitation to the dissemination of intelligence?*
- *What are the costs associated with measuring bandwidth as UAV's become operational?*
- *What are the Measures of Effectiveness (MOEs) to construct the balance between manned and unmanned aircraft from an Intelligence, Surveillance, and Reconnaissance perspective?*
- *How should the Navy balance UAV cost with capability?*
- *How should the Navy best characterize UAV costs to ensure the total cost is fully recognized?*
- *Is there value in analyzing other manned aircraft within the DOD that could provide a manned capability equivalent to unmanned at a cheaper cost?*

The Open Architecture (OA) portion of this project was based on the primary assumption that while there are savings that could potentially be achieved by using OA, especially in conjunction with a Common Architecture, the Navy must be careful when and how it chooses to use the OA. There are risks that could potentially cost more than any savings OA might be able to achieve. There are three potential areas in which using OA might result in cost savings: reuse, open source, and interoperability.

In order to quantify the effects of reuse, SLOC and equivalent SLOC (ESLOC) data from the BAMS program were analyzed. The data showed a savings of $1.4 billion, but all savings was attributed to opportunistic reuse as opposed to OA.

The open source part of the thesis drew data again from the BAMS program. By using Linux OS instead of VxWorks OS, the program was able to save $2.9 Million over the assumed 20-year life cycle of the program (assuming 25 licenses). The problem with open source code is security. More money may need to be spent on developing tighter and more layers of security, so some of the savings achieved by reusing the code may be offset by the need to write multiple types of security for the same code.

The interoperability section was focused on ground control station and the Navy's attempt at developing a Common Control System in which it owns all data rights. It is unclear whether this would in fact save money, as the BCA did not include any data rights costs, and the projected number of UAVs that would participate was reduced from six to three. The Army has developed a similar system, however it is proprietary.

6) *Programming the Laws of War: Incorporating LOAC and ROE constraints within the governance architecture of weaponized autonomous unmanned systems*

POCs: Dr. George Lucas (grlucas@nps.edu) and Mark Dankel (mpdankel@nps.edu)

Funding for this project was received well after January 1, 2012 vice 31 October, 2011, leaving insufficient time remaining in the grant period to enlist and supervise graduate students in Master's thesis research. Instead, the project team is addressing the stated goals of the pilot project by bringing together computer scientists and robotics engineers from across the country and around the world who are working on the design aspects of the LOAC/unmanned systems problem, including research teams or individual researchers from several U.S. institutions, and also from allied projects in the U.K., Australia, and France. This workshop, scheduled from November 1-4, 2012, will examine a variety of alternative engineering and design strategies, and assess the extent of progress made on the problem of guaranteeing safety, reliability and legal compliance of weaponized unmanned systems to date.

Although accommodations were arranged, meeting space reserved, tasks assigned, and a workshop format developed, two obstacles remained: first, the SECNAV instituted a freeze on all travel related to such activities nationwide, and we currently are "on hold," awaiting action on our petition for exception to the ban. Although action was due by 1 September, on Monday 24 September no action had been taken. Second, our own NPS travel office will not process ITOs or obligate funds from our grant to cover the travel of U.S. and foreign off-campus guests until after the start of the new fiscal year, 1 October 2012. Although workshop participants were remarkably patient and understanding of our dilemma, many finally needed to requested release from their commitment in order to schedule other events during the period in November originally scheduled for the workshop. Due to administrative obstacles beyond our control, this project was terminated on Monday 24 September.

7) Autonomous Multi-vehicle Tactical Surveillance and Support

POCs: Dr. Noel Du Toit (nedutoit@nps.edu) and Professor Doug Horner (dphorner@nps.edu)

Figure 6. Boeing/Insitu ScanEagle UAV

The focus of this project is extending the autonomy capability of the ScanEagle UAV platform (*see Figure 6*) by developing and implementing a secondary autopilot architecture (i.e., backseat driver). The backseat driver architecture allows the existing stock autopilot to be tasked from an onboard computer, leveraging the proven capabilities of the stock autopilot for execution. The secondary autopilot consists of software and hardware components. An onboard computer was integrated as a payload on the ScanEagle and connected to the stock autopilot. For the software, the MATLAB Simulink and Stateflow environments were used for algorithm development. These algorithms must be executed either in a real-time (RT) or non-real time (NRT) environment, for which OROCOS and ROS were used, respectively. Two interfaces with the stock autopilot were implemented: waypoint (high-level) and angular-rate (low-level) commands. A mission management module was developed (NRT) and implemented (*see Figure 7a*) and waypoint-following (high-level) mission execution has been demonstrated in simulation, and will be demonstrated in field experiments in November 2012. Additionally, a real-time path-generation capability and a path-following controller were integrated in the secondary autopilot architecture (*see Figure 7b*). The low-level interface will be demonstrated in simulation in November 2012. Limitations associated with the stock autopilot have been identified, most notably limited control over data access and update rates from the autopilot (e.g., UAV state data) and limited simulation capabilities. Switching to a commercial-of-the-shelf (COTS) autopilot is recommended as it will overcome these limitations and further facilitate cross-platform compatibility, while leveraging the secondary autopilot architecture developed in this project.

Limitations associated with the stock autopilot have been identified, most notably limited control over data access and update rates from the autopilot (e.g., UAV state data) and limited simulation capabilities. Switching to a commercial-of-the-shelf (COTS) autopilot is recommended as it will overcome these limitations and further facilitate cross-platform compatibility, while leveraging the secondary autopilot architecture developed in this project.

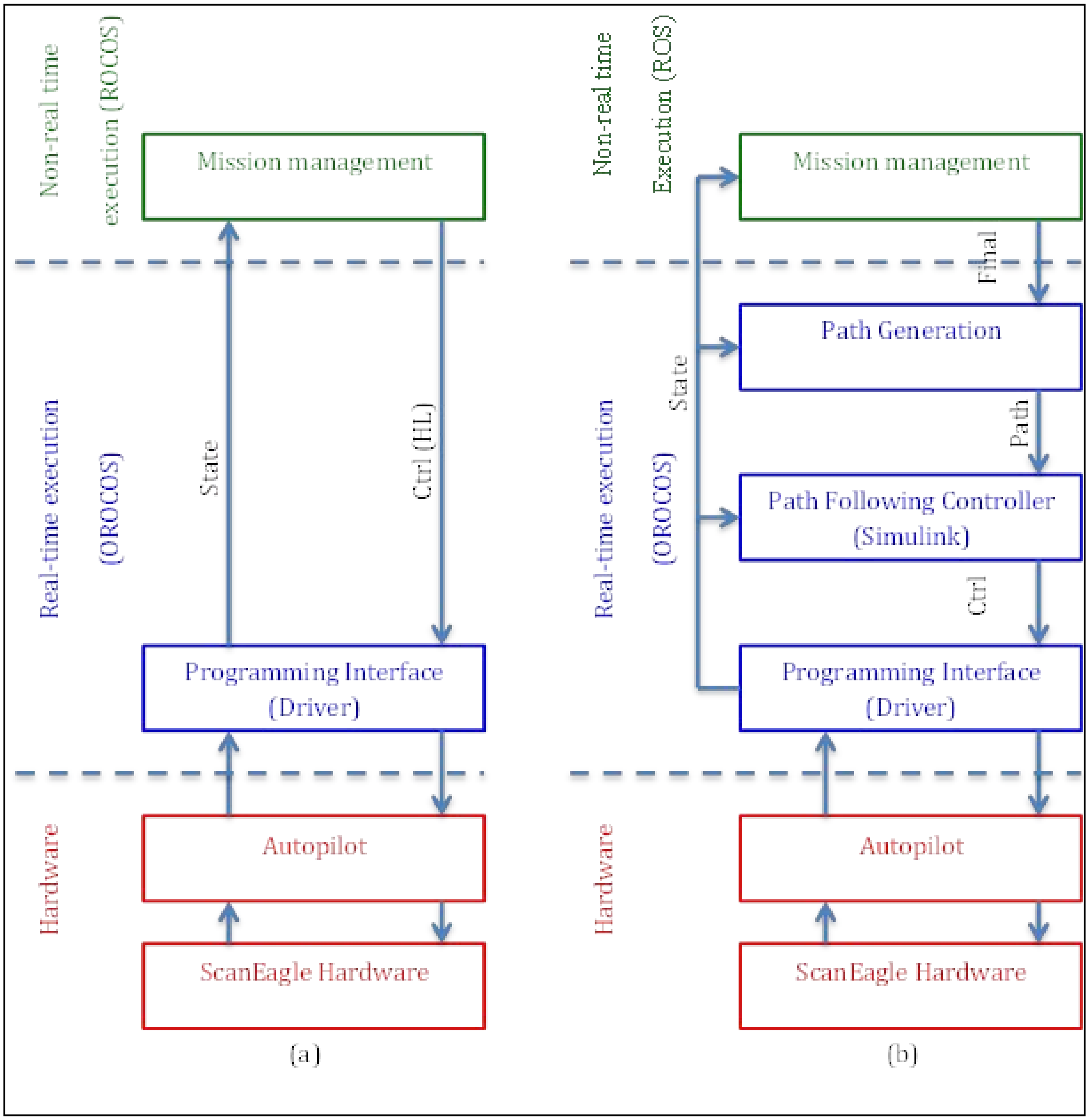

Figure 7. Secondary autopilot architecture for (a) high-level and (b) low-level control interfaces

8) Developing Novel Approaches to Quick Response Code (QR Code) Image Acquisition using Live-streaming 4K Ultra-high Resolution 60p Camera Systems
POCs: Jeff Weekley (jdweekle@nps.edu) and Dr. Don Brutzman (brutzman@nps.edu)

This project proposes a novel approach to acquiring QR Code images using emerging ultra-high resolution, high-frame rate, live-streaming 4K digital video camera systems from static and time-varying QR Codes at various distances and presentation formats as preliminary tests for future applications in field exercises and relevant operations. The goal is to perform a series of QR Code image acquisition tests using emerging 4K live-streaming camera systems. The tests include both laboratory bench tests for initial system configuration and in-field tests to determine performance characteristics of the camera system and various QR Code schemes. Preliminary results were presented at the TENTH International Mine Warfare Technology Symposium in May 2012 in Monterey CA.

Figure 8. Research Associate Jeff Malnick tosses a QR code spinning in the air to demonstrate the ability of the 4K Camera System to freeze highly dynamic imagery suitable for the capture of QR Codes on fast moving objects.

<u>Initial tasks:</u>

- Establish Initial System Configuration, Tests and Results
- Procure appropriate loaner camera systems under existing or new LPCRADA
- Establish initial bench tests to include QR Code image acquisition, image processing and associated workflows
- Conduct limited field experiments to establish likely operational parameters of QR Code Reader 4K Camera System
- Present Preliminary Results at the TENTH International Mine Warfare Technology Symposium, May 7-10, 2012 in Monterey, CA

<u>Follow-on Tasks:</u>

- Field Deploy, Test and Evaluate
- Evaluate Suitability of System for purchase and integration into NPS and Navy-owned Unmanned Systems and Surrogates (e.g. MZ-3A Airship)
- Operational experience guides ongoing development and deployment

IMPACT/APPLICATIONS

At SECNAV direction, CRUSER's purpose is to build an interdisciplinary consortium to address all aspects of employing unmanned systems in an operational environment. That community now exists and is growing.

RELATED PROJECTS

1) ARSENL

The Advanced Robotic Systems Engineering Laboratory (ARSENL) represents a diverse academic and research group at the Naval Postgraduate School, emphasizing that robotic and unmanned systems merit a holistic, multi-disciplinary approach for their design, their employment, and their future concepts. Led by Assistant Professor and CRUSER Director of Research and Education, Dr. Timothy Chung in the NPS Systems Engineering Department, ARSENL comprises students representing all naval unmanned systems domains (sea, subsurface, aerial, amphibious, and ground robotics), five countries in addition to U.S. Navy and Marine Corps students, and from over six different academic departments across the NPS campus. Associated research projects range from algorithms for improved autonomy of UAV swarms to design and modeling of surf-zone crawling robots to assessment of unmanned capabilities for subsurface operations. Further, ARSENL facilitates innovation and camaraderie through opportunities for information exchange at weekly group meetings, where interactions can lead to ideas and better mutual understanding.

2) A Swarm vs. Swarm Grand Challenge Competition

CRUSER also supports the active development of live-fly experimentation capabilities for many-robot unmanned aerial vehicle (UAV) systems research ongoing at the Naval Postgraduate School. Leveraging access to unique resources, such as facilities at Camp Roberts, Calif. and frequent experimentation events, the Many vs. Many (MvM) Autonomous Systems Testbed provides the infrastructure to holistically explore many-robot systems research in operationally realistic settings, and challenges engaged researchers to more actively and expediently translate theory to practice. The MvM Testbed is designed to integrate technological advances in hardware (inexpensive, expendable); software (open source, open architecture); networking (dynamic information management); and operational concepts (tactics, command and control); and leverage many corollary efforts.

Development of this testbed also highlights NPS' focus area of generating new concepts of operations, especially in the context where they may face non-cooperative or even adversarial systems. Enabling technologies that provide the autonomous abilities to perceive, recognize, and respond to these players will further enhance their operational relevance. In this context, the NPS Aerial Swarm project is designed to leverage the MvM Autonomous Systems Testbed to explore practical and operationally relevant avenues to counter these "swarm" opponents, and to pursue validation of advanced theoretical approaches concurrently. The vision for the Swarm vs. Swarm project is to push the boundaries of many-robot systems research with an ambitious initiative culminating in live-fly field experiments involving 50 vs. 50 UAVs by 2015. This project significantly leverages existing infrastructure through the NPS Field Experimentation Cooperative and CRUSER programs, and offers a venue for concept generators, researchers, and operators to holistically address many technologically and operationally challenging problems in a field experimentation context.