Land, Sea, and Air Unmanned Systems Research and Development at SPAWAR Systems Center Pacific

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ABSTRACT

The Space and Naval Warfare (SPAWAR) Systems Center Pacific (SSC Pacific) has a long and extensive history in unmanned systems research and development, starting with undersea applications in the 1960s and expanding into ground and air systems in the 1980s. In the ground domain, we are addressing force-protection scenarios using large unmanned ground vehicles (UGVs) and fixed sensors, and simultaneously pursuing tactical and explosive ordnance disposal (EOD) operations with small man-portable robots. Technology thrusts include improving robotic intelligence and functionality, autonomous navigation and world modeling in urban environments, extended operational range of small teleoperated UGVs, enhanced human-robot interaction, and incorporation of remotely operated weapon systems. On the sea surface, we are pushing the envelope on dynamic obstacle avoidance while conforming to established nautical rules-of-the-road. In the air, we are addressing cooperative behaviors between UGVs and small vertical-take-off-and-landing unmanned air vehicles (UAVs). Underwater applications involve very shallow water mine countermeasures, ship hull inspection, oceanographic data collection, and deep ocean access. Specific technology thrusts include fiber-optic communications, adaptive mission controllers, advanced navigation techniques, and concepts of operations (CONOPs) development. This paper provides a review of recent accomplishments and current status of a number of projects in these areas.

Keywords: Navy, SPAWAR, robotics, unmanned systems, UGV, USV, UAV, UUV

1. INTRODUCTION

The Space and Naval Warfare Systems Center Pacific (SSC Pacific) and its predecessor organizations have been pioneers in the unmanned systems field for over 45 years. This legacy began with unmanned underwater vehicles (UUVs) in the early sixties,[1] and was extended to include unmanned ground vehicles (UGVs) in the early eighties. Initial work involved the development of teleoperated dune buggies and HMWWVs for the US Marine Corps,[2,3] followed by autonomous indoor and outdoor security robots for the US Army.[4,5]

In the late nineties, SSC Pacific built six small teleoperated UGVs for use by Army engineers in tunnel, sewer, cave, and urban structure reconnaissance. These early systems participated in several experiments at Fort Leonard Wood, MO, Fort Drum, NY, and Fort Polk, LA.[6] In April 2002, SSC Pacific provided four robots to Navy Explosive Ordnance Disposal (EOD) Mobile Unit 3 for use in Operation Enduring Freedom in Afghanistan.[7] The San Diego robotics group was designated a "Center of Excellence for Small Robots" by the Office of the Secretary of Defense (OSD) shortly thereafter.

Following the World Trade Center attacks in 2001, DARPA transitioned their Tactical Mobile Robot (TMR) program to SSC Pacific, initiating a focused effort to upgrade the autonomy and functionality of man-portable robots. In 2002, relevant components of UGV autonomy were adapted for use on unmanned surface vehicles (USVs), and the lab's first attempts at collaborative behaviors took the form of UGV/UAV marsupial integration. The "Warfighter's Associate" concept for proximal human-robot teaming was introduced at the SPIE Mobile Robots XVII conference in Philadelphia, PA, in October 2004,[8] and remains an important area of continued emphasis.

SSC Pacific now has over 70 engineers and scientists performing research, development, and testing of unmanned systems supporting Army, Navy, and Marine Corps customers. This paper reviews recent accomplishments and provides the current status of several of our unclassified development efforts across all operational domains (i.e., air, land, and sea).

2. GROUND-BASED SYSTEMS AND PROJECTS

2.1 Autonomous Navigation for Small UGVs (ANSU)

The goal of the ANSU project is to increase the warfighter's capability by developing, maturing, demonstrating, and harvesting technologies that will significantly increase the functional capabilities of small UGV systems. Many of these autonomous capabilities have already been demonstrated on larger systems in R&D environments, and those technologies will be leveraged where possible. However, small robots provide unique challenges that the larger systems do not, including severe size, power, and weight constraints. Most of the larger systems currently use sensors that cannot be supported on the man-portable robots, and similar sensors that meet the size, weight and power requirements of small robots do not provide comparable quality of data. Therefore, in addition to the maturing of smaller sensors, ANSU also focuses on the development or adaptation of software appropriate for these smaller sensors and platforms.

ANSU has recently demonstrated a number of autonomous navigation behaviors to EOD users using the Naval Explosive Ordnance Disposal Technology Division (NAVEODTECHDIV)'s Man-Transportable Robotic System (MTRS) robots. These behaviors include: waypoint navigation (with and without obstacle avoidance), guarded tele-operation, retro-traverse, point-and-click to drive, visual odometry, and three-dimensional (3D) scene building for improved operator situation awareness. The team is also continuing to develop improved autonomy functions and sensors, including working with General Dynamics Robotic Systems (GDRS) to develop a miniature multi-axis scanning LADAR, and with the Jet Propulsion Laboratory (JPL) to continue improvements to a stereovision and obstacle-detection system (see Figure 1).

Figure 1. The JPL stereo vision sensors on an MTRS PackBot.

2.2 Urban Environment Exploration (UrbEE)

The UrbEE project focuses on developing technologies required for small UGVs to autonomously navigate within urban environments. UrbEE primarily addresses the navigation and operator control of the robotic platform. Autonomous navigation behaviors have been developed by the robotics R&D community over the past few decades, producing a variety of technological approaches to navigation and mapping in unknown or partially known two-dimensional worlds. Historically though, these prototype systems have been developed for either an outdoor or an indoor scenario, but not for both. In an urban environment, a robotic system will need to traverse seamlessly between both environments while maintaining accurate localization and effective mapping.

UrbEE approaches this problem through the use of multiple localization techniques, including Kalman Filter-based inertial navigation, laser-based simultaneous localization and mapping (SLAM), and GPS. Optimization techniques are used to combine the outputs of these techniques to maximize the accuracy of localization in any situation, such as loss of GPS in "urban canyons". This project also addresses the need for small robots to be able to effectively navigate conditions typical of urban terrain, such as curbs, stairs, and rubble. FY08 results from tests at military operations in urban terrain (MOUT) training sites have validated the ability of the system to bound localization error at all times to less than 2% of distance traveled, and also to autonomously explore and map cluttered buildings with minimum user assistance. The resulting SLAM maps are automatically registered with aerial imagery (see Figure 2). Work in FY10 will include mapping multiple buildings, traversing stairs, and mapping in three dimensions.

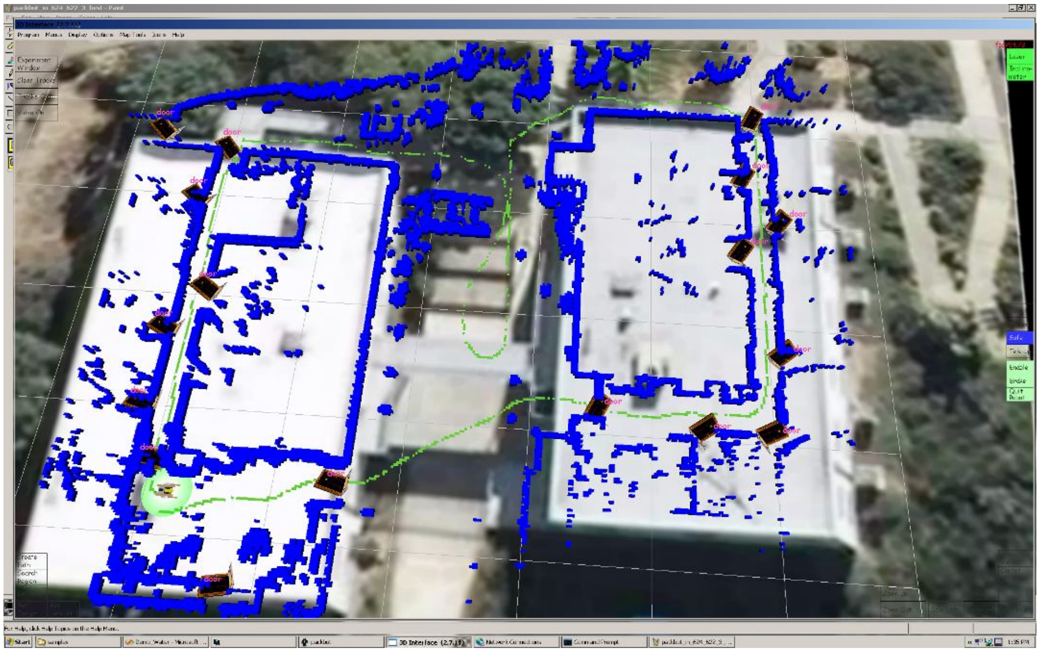

Figure 2. A SLAM map registered with aerial imagery in real time.

2.3 Urban Environment Modeling (UrbEM)

The UrbEM project aims to develop, mature, and demonstrate technologies that will provide rich 3D models of complex urban environments from the ground perspective, mainly using sensors normally found on UGVs. The models may be used for UGV mission planning, navigation, and localization, and possibly by the warfighter as a mission planning and training tool. The project will build upon and transfer technology from a variety of sources, including universities, DARPA programs, private industry, DoD, and other Government organizations. Under UrbEM, we have evaluated various 3D large-scale modeling technologies, such as laser scanning, structure-from-motion, multi-view stereo, and spatial-phase video. Currently, we are working with the University of Washington to adapt their structure-from-motion technology (which was licensed to Microsoft for PhotoSynth) in conjunction with their multi-view stereo technique[9] to use images captured from UGV cameras (see Figure 3). We are also working on scaling the algorithms to thousands of images, speeding up the pipeline, and intelligently simplifying the models to decrease the size of output files.

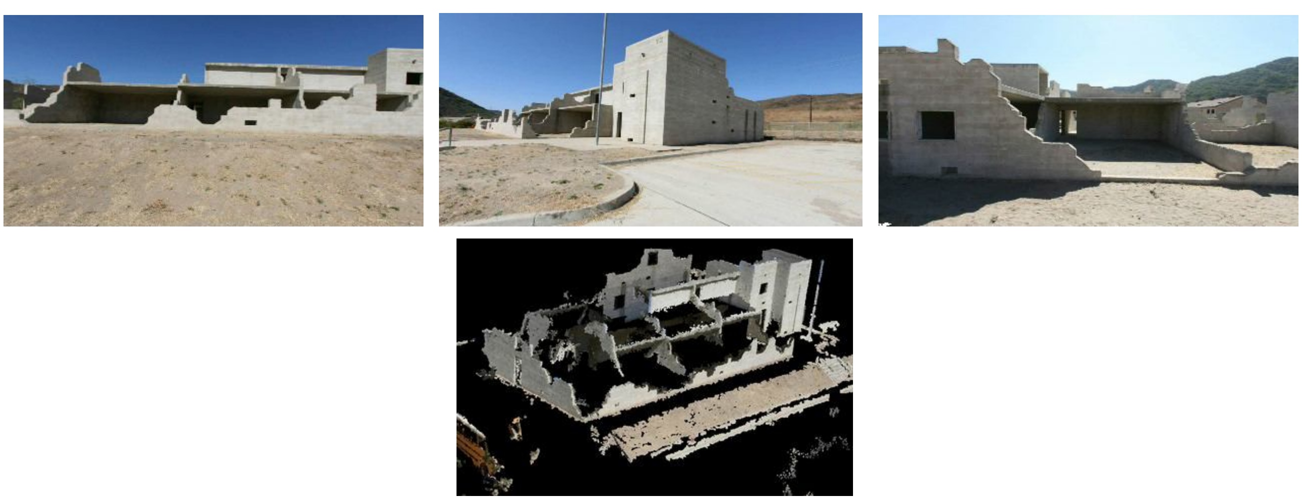

Figure 3. (Top) Three samples from a series of photographs of a structure at the Camp Pendleton MOUT site. (Bottom) the resulting 3D model generated by multi-view stereo techniques.

2.4 3-D Visualization for EOD Robots

The purpose of this project is to develop, mature, demonstrate, and transition technologies that will provide the EOD UGV operators with an improved situational-awareness and visualization capability for manipulation. Current EOD UGVs rely exclusively on live streaming video from one or more monocular video cameras for manipulation tasks. This single-camera narrow field-of-view makes it very difficult for EOD operators to judge the distance from the end effector to the object they are trying to grasp or manipulate. The system under development will provide a high-resolution 3D model of the object of interest during a mission in near real-time, while the position of the UGV and manipulator relative to the object will be calculated in real-time. The 3D model of the object as well as models of the UGV and manipulator will be presented to the operator on the controller user interface in a virtual environment that very accurately reflects the real system. This will allow the operator to view the object and the UGV/manipulator from any viewpoint, with far greater situational awareness.

We have begun evaluation of various 3D scene modeling technologies, including structure-from-motion, multi-view stereo, laser scanning fused with color image data, spatial phase video, registration software/algorithms, and visualization techniques/applications. Figure 4 shows another application of the multi-view stereo technique applied to smaller objects, in this case a mockup of an improvised explosive device (IED) hidden between a tire and a pallet.

Figure 4. (Top) Three samples from a series of photographs of a simulated IED. (Bottom) the resulting 3D model generated by multi-view stereo technique.

2.5 Autonomous Payload Deployment System (APDS)

APDS is an extension of the Automatically Deployed Communication Relays (ADCR) project executed between 2004 and 2009.[10] ADCR aims to provide an automatic radio relaying system that can be used with any manned or unmanned vehicle with an IP-based communication system. The vehicle-mounted relay deployment module monitors the signal strength of the closest leg of the mesh communication network between the vehicle and the control station, and using a predictive filter, automatically drops relay nodes where needed to maintain a robust link. The relay node self-rights and raises an antenna upon deployment (see Figure 5). Four prototype systems have been built and demonstrated. A second-generation design, with smaller relay nodes and using more secure, higher-bandwidth radio cards, is in the final testing stage. The project won the 2008 Office of the Secretary of Defense (OSD) Office of Technology Transition and DoD

TechMatch Hot Technologies Contest, and is now available for licensing through the SSC Pacific Technology Transfer Office.

Figure 5. A first-generation ADCR system mounted on a PackBot EOD robot, with a deployed relay node.

APDS takes the ADCR concept one step further, enabling the vehicle-mounted deployment module to drop networked stand-alone sensors, IR illuminators, ammunition, food, first-aid kits, or any other payload that may fit within the form factor. Payloads from single to triple height can be accommodated. The deployment action could be triggered by pre-programmed response to environmental conditions or by remote control. A networked video and ground vibration sensor node and an empty container node are being fabricated. The system is being designed to be extremely modular and flexible, with the intention of allowing third-party developers to build upon the system infrastructure to develop additional types of payload as required. Other networking radios, including some versions of the Joint Tactical Radio Systems (JTRS), can also replace the current network radios when they become available.

2.6 Man-portable Intelligence, Surveillance, and Reconnaissance (ISR) Robot

The goal of the Man-Portable ISR Robot project is to develop and test a prototype UGV with enhanced functionality that specifically supports persistent surveillance and reconnaissance applications. New operational capabilities derived from this effort will include the ability to conduct continuous covert unmanned surveillance from a remote location (analogous to a human occupied observation or listening post), plus the ability to utilize long-range teleoperation through non-line-of-sight communications and semi-autonomous navigational behaviors. Near-term development objectives include mobile platform fabrication, integration of point-to-point wireless radio communications, and development of a small diesel-electric hybrid system to power traction and onboard electronics.

The base ISR robot platform will use a modified version of Autonomous Solutions CHAOS™ high-mobility robot[11] (see Figure 6). The CHAOS platform will be adapted for use with an integrated hybrid power system intended to provide the user with over 72 hours of continuous operation without refueling or recharging batteries. The heavy-fuel/electric hybrid system is needed to attain the energy and power densities required to maintain 3 days of continuous operation. The ongoing development effort also includes design and fabrication of a noise suppression system for the diesel generator. While capable of operating on virtually silent battery power for limited periods of time, continuous covert operation will require a reduction in generator noise to below 60 dB. Both active and passive noise suppression are being explored as potential solutions.

Figure 6. Autonomous Solutions CHAOS platform.

Various digital wireless communication solutions for the ISR robot are currently undergoing field evaluation with the objective of transmitting real time video and command instructions up to 20 kilometer distance. Final selection from among several candidate radio systems will take place during late spring 2009. The solution will involve use of an extendable mast that can be raised remotely to increase antenna height to 2 meters or more along with data compression schemes to limit required bandwidth.

Plans for the project include integration of a configurable sensor suite consisting of optical and acoustic sensing devices. The system will also combine computer-assisted operator control with some basic navigational autonomy to facilitate long-range teleoperation under challenging communications conditions. The project will culminate in 2010 with multiple user trials and one or more operational experiments employing the prototype system in simulated mission scenarios.

2.7 Human Presence Detection (HPD)

The goal of the HPD project is to increase the ability of UGVs to detect and localize humans while moving, both for tactical purposes as well as for safe robot navigation when operating in the proximity of humans. HPD addresses both the selection of appropriate hardware to detect humans as well as the algorithms used to analyze the sensor output. The project has focused on providing different solutions for small and large UGVs given the differences in power, weight, and size constraints between vehicle classes. The large-vehicle portion of the project is using LIDAR and radar systems to detect people during vehicle motion, while the small-vehicle portion of the project pursues the use of low-cost monocular and stereo thermal and color imagery in conjunction with image processing algorithms (see Figure 7). The HPD payloads produced by this project may be useful in satisfying requirements for human detection in programs such as the Army's Future Combat System (FCS) and Mobile Detection Assessment Response System (MDARS). We are conducting this work in collaboration with General Dynamics Robotic Systems and Sarnoff Corporation. FY08 results from SSC Pacific and Sarnoff indicate that low-cost sensors for small robots can detect people with approximately 90% detection rate and low false alarm rate in any lighting conditions independently of vehicle motion. FY09 work will focus in further increasing the performance and creating a prototype sensor package sufficient for real-world testing on fielded vehicles.

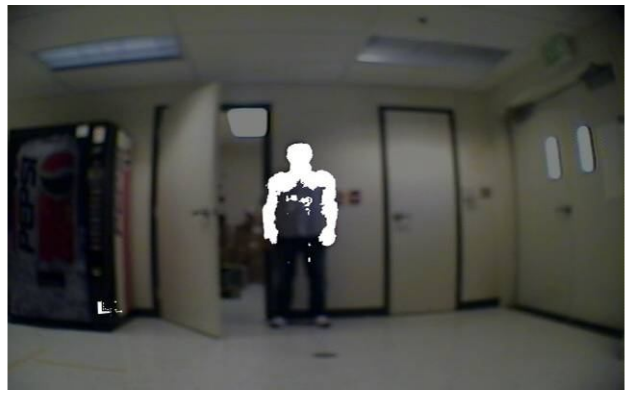

Figure 7. A person detected through fusion of color and thermal imagery.

2.8 Multi-robot Operator Control Unit (MOCU)

The Multi-Robot Operator Control Unit (MOCU)[12,13] is a graphical operator-control software package that allows simultaneous control of multiple heterogeneous unmanned systems from a single console (see Figure 8). MOCU has been designed to address interoperability, standardization, and customization issues by using a modular, scalable, and flexible architecture. MOCU has been used as the unmanned systems controller for the Intelligence Community UGVx project (2001), the Night Vision and Electronic Sensors Directorate Remote Robotic Reconnaissance Vehicle project (2002), the OSD Spartan ACTD (2003), the OSD Joint Unmanned Systems Common Control ACTD (2004), the Product Manager for Force Protection Systems (PM-FPS) Family of Integrated Rapid Response Equipment project (2005), and the Navy's Littoral Combat Ship (LCS) program (2007), for both the Mine Warfare mission as well as the Antisubmarine Warfare mission. It has also been selected as the OCU software for NAVEODTECHDIV's next-generation Advanced EOD Robotic System (AEODRS) robots, and was ranked highest in both "technology" and "universality" in a OSD

Figure 8. Screen-shot of MOCU configured as a multi-vehicle (UAV/USV/UGV) controller; video stream is from currently selected man-portable UGV.

Joint Ground Robotics Enterprise (JGRE)-commissioned study of common OCUs.[14]

A third-generation product, based upon a publish/subscribe architecture, is under development that completely uncouples the human interface from the core management software, thus allowing even more flexibility in user customization of the product. In addition, SSC Pacific is working under the ONR Capable Manpower Future Naval Capability program to develop a user interface module specifically designed around emerging work in human-computer interfaces (HCI). A basic goal of the HCI effort is to improve the interface between users and computers by making computers more usable and receptive to the user's needs. This work will result in plug-in MOCU user interface modules that present clear and consistent displays, minimize visual scanning and search, have primary focus displays (e.g. video, route, sensor), transparent overlays (e.g. heads-up displays), and drill-down amplified formats with one-button call-up. They will also provide *Task Management* including task existence and completion status, *Attention Management* using visual and auditory prompts, *Control-Display Compatibility* employing similar layouts for each vehicle, and *Proximity* implemented as adjacent or overlaid information including route, waypoints, vehicle status, and video.

2.9 Mobile Detection Assessment Response System (MDARS)

The MDARS program is executed by PM-FPS out of Fort Belvoir, VA. SSC Pacific has been involved in MDARS since the late 1980’s as both the developer of the command and control system (the Multiple Resource Host Architecture or MRHA) and as the Chief Engineer for technical development and integration.[15] MDARS initially had an interior (warehouse) mission and an exterior (depot) mission, but the interior application was put in abeyance in the late 1990’s due to a lack of continued user requirements. The exterior program has been successful at fielding (in a limited rate of initial production during FY09) the first semi-autonomous ground robot for use by DoD (see Figure 9). The MDARS exterior patrol unit vehicle (PUV) is an advanced UGV capable of self-guided navigation using differential GPS and inertial sensors, along with LIDAR-based obstacle detection and avoidance capabilities, to autonomously patrol high-value storage facilities for Joint Service and Inter-Agency use. MDARS supports both physical security and automated inventory management payloads; it has also demonstrated a less-lethal capability using dual FN303 (“paintball”) guns queued by the on-board personnel-detection radar. MDARS is controlled by the MRHA, which provides for simultaneous control and supervision of multiple platforms from a single C2 console. MDARS users include the U.S. Army Military Police School and an expanding list of non-military agencies (e.g., DOE). Planned product improvement for the MDARS PUV includes a detection-on-the-move capability as well as increased platform speed and longer-range detection/assessment sensors.

Figure 9. PM-FPS MDARS exterior PUV at Hawthorne Army Depot in Nevada during operational testing.

2.10 Joint Force Protection Advanced Security System (JFPASS) JCTD

JFPASS is an FY08-start JCTD intended to demonstrate an integrated force protection system-of-systems for expeditionary, semi-fixed, and fixed base missions (see Figure 10). SSC Pacific is the Technical Lead for the JCTD, and is the provider of the primary C2 system known as the Joint Battlespace Command and Control System (JBC2S),[16] which is a MOCU derivative. The JFPASS JCTD has leveraged prior work performed under the Force Protection Joint Experiment (FPJE) managed by Joint Program Manager Guardian (JPMG) and funded by the Physical Security Equipment Action Group (PSEAG). The FPJE was an accelerated series of formal experiments, occurring over FY07-FY08, aimed at evaluating the effectiveness of COTS/GOTS physical security equipment integrated as a system-of-systems applied to the force protection mission operated in accordance with the Integrated Unit, Base, and Installation Protection (IUBIP) concept of operations. The FPJE successfully demonstrated the effectiveness of using standards-based protocols (i.e., SEIWG ICD-0100) to integrate a collection of over 15 different systems into a versatile force

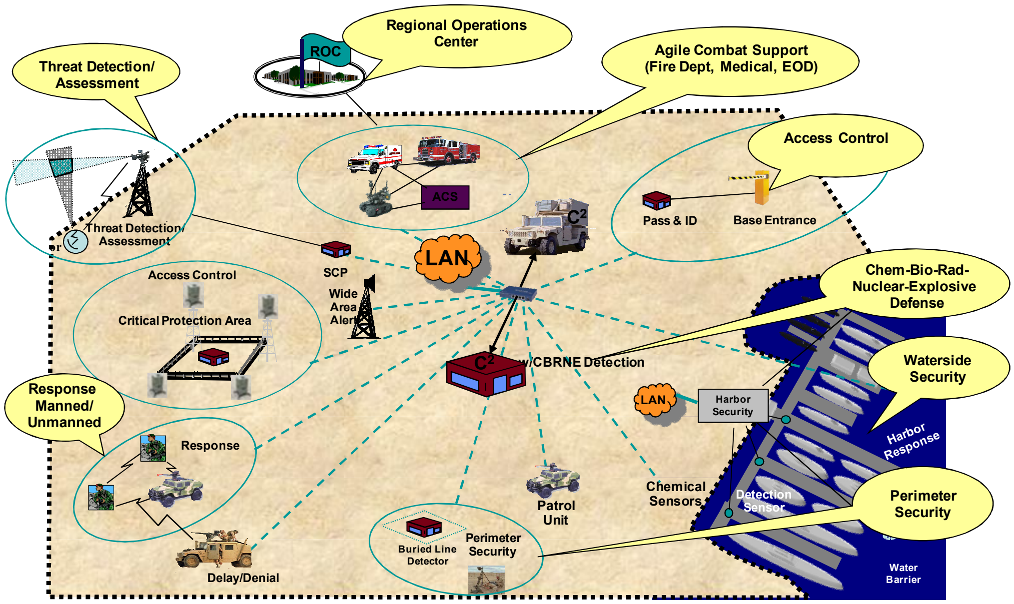

Figure 10. JFPASS Operational View (OV-1).

protection suite under the control of JBC2S. JBC2S can currently interface to and control any ICD-0100 compliant device including ground surveillance radars, unattended ground sensors, fiber-optic fence sensors, unmanned ground vehicles, remotely operated weapon systems, personnel tracking systems, chemical and radiation sensors, multiple camera systems, and a variety of U.S. Air Force TASS sensors. The JFPASS JCTD is further maturing the systems architecture developed under the FPJE by extending data distribution and sensor fusion capabilities. The U.S. Navy (NSWC Dahlgren) is the JCTD Technical Manager, the U.S. Air Force in Europe (USAFE) is the Operational Manager, and JPMG is the Transition Manager. SSC Pacific is currently leading integration efforts for the first JCTD Operational Demonstration planned for Q3 FY09. The supporting infrastructure for a leave-behind capability in the USAFE area of responsibility is currently being installed by SSC Atlantic.

2.11 Networked Remotely Operated Weapon System (NROWS)

NROWS is a networked weapons platform designed to provide a remote lethal response to intruders. The system can be UGV deployed (see Figure 11) or fixed in place to provide a remote response capability for a wide variety of security operations and other tactical missions. NROWS provides field or base commanders with a real-time unattended weapons pod that quickly extends the delay/denial response capabilities at high-value installations or in tactical scenarios. NROWS will be integrated with autonomous surveillance, detection, and automated target tracking to enable timely mission-essential information and response to enemy activity. The NROWS system uses a distributed TCP/IP network control-communication architecture, which allows for flexible integration and operation of multiple platforms from a single control station. Communications between the remote weapons platform and control station can be established in a direct link or wirelessly. The system can accommodate a wide variety of lethal and less-lethal small arms. FY08 effort demonstrated the system in a wide variety of configurations, including wall-mounted, pop-up, and vehicle-mounted. In addition, the NROWS systems have been configured to inter-operate with other command-and-control protocols such as the Multiple Resource Host Architecture (MRHA) and are being demonstrated as part of the JFPASS field experiments.


Figure 11. A less-lethal NROWS mounted on an MDARS vehicle.

2.12 Advanced EOD Robotic Systems (AEODRS) Communications Study

The purpose of this study is to assess and evaluate promising wireless radio-frequency (RF) communication technologies suitable for unmanned vehicles employed in EOD operations. Particular emphasis is given to wireless systems currently being fielded as part of DoD programs of record and to evolving wireless technologies being developed by DARPA.

All currently fielded EOD UGVs are teleoperated, necessitating significant bidirectional high-bandwidth communications between the robotic vehicle and the OCU. Two specific operational issues have served to increase the focus on EOD robot communication systems. The first of these is the increasing use of Counter Radio-Controlled Improvised Explosive Device Electronic Warfare (CREW) systems in theater. Another issue has been the EOD community's demonstrated preference for using wireless rather than tethered means of communications.

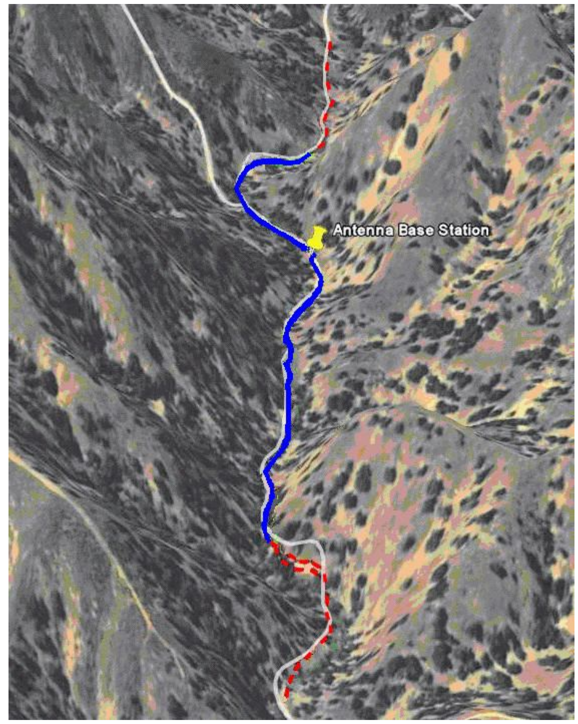

Figure 12. Example display of radio field test results showing active (blue solid) and broken (red dashed) communication links between a static base station and mobile platform

The initial phase of the project, completed in March 2009, included a market survey focused on candidate wireless systems with the potential to meet AEODRS and Man Transportable Robotic System (MTRS) requirements, particularly with respect to such functional areas as RF performance (range, data rate, latency, environmental conditions); spectrum coordination; information security; interoperability with other DoD systems and networks; and compatibility with CREW systems. The survey is intended to support risk-reduction efforts for the program and as an aid to PMS-EOD in its strategy for developing a common wireless communication system for EOD robotic systems.

Follow-on assessment, currently in progress, includes field testing candidate systems in a variety of physical environments. To date, such tests have focused on range performance under line-of-sight and non-line-of-sight conditions, in both urban and rural terrain (see Figure 12).

2.13 Robotic Systems Pool / Outreach Centers

The Robotic Systems Pool (RSP) is a ready inventory of robotic vehicles, payloads, and related components that SSC-Pacific makes available on loan to requesting users in order to support research and development, experimentation, evaluation, training, and technology transfer.[17] RSP customers include DoD organizations from all branches, first responders and public safety organizations involved in law enforcement, fire fighting, border security, hazardous materials response, etc., along with in developers from academia, industry, and government. One of the chief benefits of the RSP program is that it provides users a low-risk quick-turnaround opportunity to gain access to new technologies that they might otherwise not see for years. The feedback attained from having operational subject matter experts evaluating technology at a relatively early stage can be invaluable in helping to mature, refine, or evolve technology beyond its current capabilities; ultimately making the technological design more relevant to user needs across multiple operational domains. The RSP also serves to facilitate technology adoption by overcoming some of the traditional barriers to user trials, again serving to bridge the gap between technology users and technology developers.

Over the past year, and in partnership with Office of the Assistant Secretary of Defense (OASD) for Homeland Defense and America's Security Affairs (HD&ASA) Technology Transfer Office, RSP assets have been made more accessible to regional first responders through the Regional Technology Outreach Center (RTOC) Program. An initial pilot-program Outreach Center was established in 2008 within the Public Safety Academy of Northeast Indiana, located in Fort Wayne, Indiana. The Center facilitates equipment loans, training, and technology demonstrations for first responders throughout the region. Additional RTOCs are being planned for locations in nine states, including two additional centers that will be established in 2009 (see Figure 13).

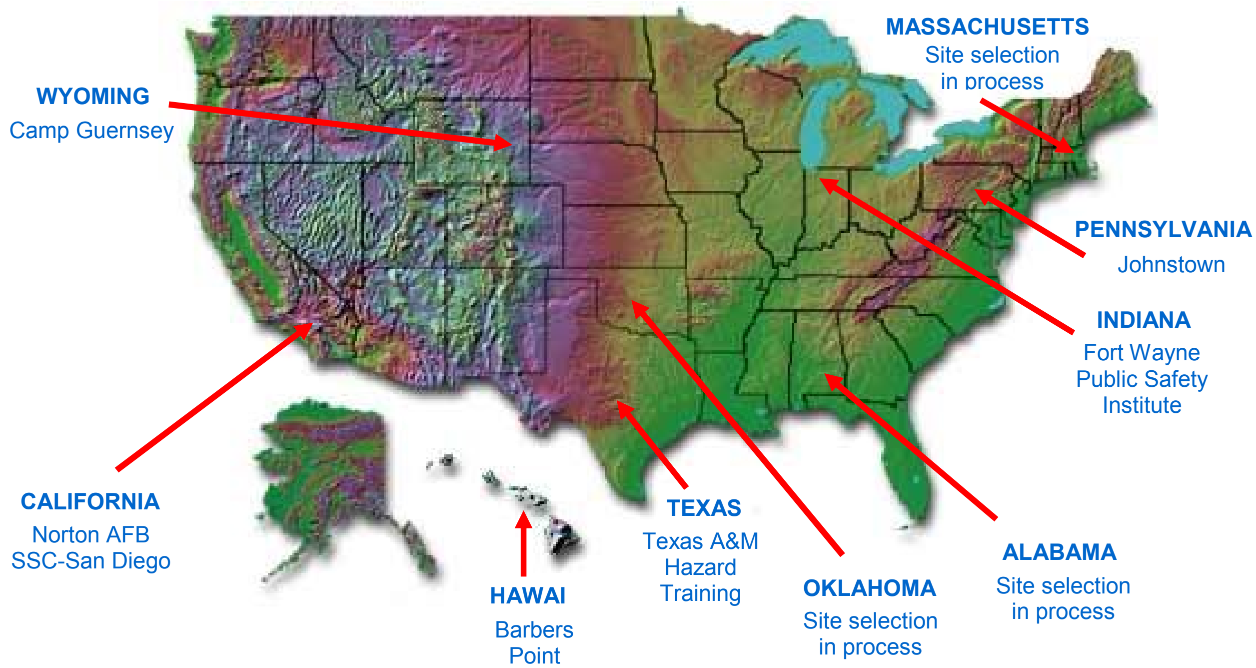

Figure 13. Current and planned Outreach Centers.

2.14 Mobile Robotics Community (MRC) Web Site

The Mobile Robotics Community (MRC) is a Web-accessible resource created for sharing information, experience, and technology within the robotics community. It replaces and expands upon the former SSC Pacific Mobile Robot Knowledge Base web site. It is intended to serve as a centralized knowledge repository and collaboration tool used to manage a rapidly growing but dissociated body of knowledge. The MRC has been designed from the start to accommodate open contributions and distributed authorship. Features include: multilevel access control, user-defined trusted groups, forums, a knowledge wiki, a technology database, group collaboration tools, an events calendar, and knowledge discovery and routing tools. The current implementation can be viewed at: *http://www.gorobot.org*.

3. AERIAL SYSTEMS AND PROJECTS

3.1 Joint Collaborative Technologies Experiment (JCTE)

JCTE is a joint effort between SSC Pacific, the Air Force Research Lab (AFRL), and the Army Aviation and Missile Research Development and Engineering Center (AMRDEC). The objective is the integration of collaborative technologies that support teaming of manned and unmanned systems across multiple domains (mainly air and ground). The project focuses on developing capabilities for communications, sustainment, and engagement with Joint Architecture for Unmanned Systems (JAUS)-compliant systems. Under this umbrella, AFRL is demonstrating beyond-line-of-sight (BLOS) communications range extension through a UAV-borne relay, AMRDEC is experimenting with target identification and lethal engagement from unmanned vehicles, and SSC Pacific is developing the Autonomous UAV Mission System described below.

3.2 Autonomous UAV Mission System (AUMS)

AUMS, as part of the JCTE, aims to provide a means of forward staging, launching, recovering, refueling, and re-launching of small vertical-takeoff-and-landing (VTOL) UAVs.[18] The AUMS platform can operate from surface or ground vehicles, manned or unmanned, or stand-alone in a fixed-site installation. The system is meant to provide autonomous operations to increase operator safety, reduce operator workload, and increase the UAV's time on station. A mission scenario may include sending a remotely controlled or waypoint-designated autonomous UGV equipped with the AUMS platform into a hostile or contaminated area. There it can launch a UAV, recover it when the UAV is low on fuel, refuel, and re-launch the UAV multiple times, significantly increasing mission time.

Figure 14. The AUMS platform mounted on a remote-controlled HMMWV and supporting a Mongoose UAV.

To date the AUMS team has developed several modular, automated launch-and-recovery prototype platforms as part of a spiral design, and refueling systems for use with a variety of Class 1 and Class 2 VTOL UAVs. Collaborative autonomous command-and-control behaviors for AUMS and VTOL UAVs have also been developed using MOCU and JAUS. In 2009 the complete AUMS mission profile (autonomous launch, recovery, refuel, and re-launch) was demonstrated using the Mongoose UAV (see Figure 14).

4. MARITIME SYSTEMS AND PROJECTS

4.1 Unmanned Surface Vehicle (USV)

The US Departments of Defense (DoD) and Homeland Security (DHS) are increasingly interested in the use of unmanned surface vehicles (USVs) for a variety of missions, including Special Warfare force projection and reconnaissance, mine counter measures, port and harbor surveillance and security, marine hydrographic surveying, and environmental sensing. In order for USVs to fill these roles, they must be capable of a relatively high degree of autonomous navigation. SSC Pacific is developing core technologies required for robust USV operation in a real-world environment, primarily focusing on autonomous navigation, obstacle avoidance (OA), and path planning.[19,20]

Our obstacle avoidance approach is based on a near-field or reactive OA component and a far-field or deliberative OA component, operating simultaneously. The function of the deliberative component is to continuously modify the existing route to plan around obstacles (including moving obstacles) detected with long-range sensors, making use of nautical charts and following maritime rules-of-the-road. Primary sensors for the deliberative OA component include marine radar and the Automatic Identification System (AIS). The reactive OA component is responsible for avoiding obstacles in close proximity to the vehicle regardless of the vehicle's mode of operation. Sensors for the reactive component include monocular vision, binocular vision, radar, and LIDAR. Currently we are investigating the use of a Velodyne HDL-64E LIDAR with a 360° by 26.8° field of view. This LIDAR can clearly image obstacles as small as a kayak at 50 meters and larger obstacles at up to 100-120 meters (see Figure 15).

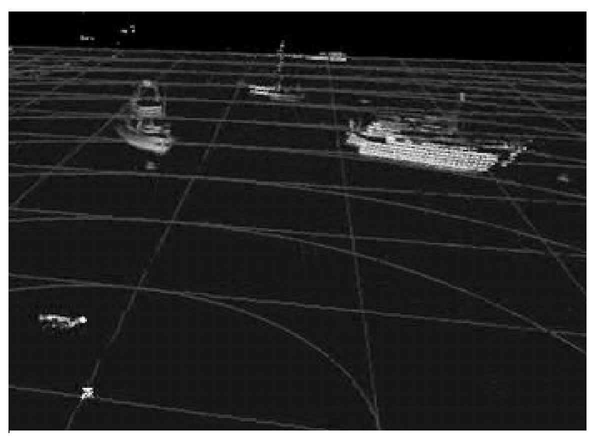

Figure 15. Scene from San Diego Bay as imaged by the Velodyne LIDAR.

4.2 Hybrid Remotely Operated Vehicle (HROV)

The Hybrid Remotely Operated Vehicle (HROV) Nereus (see Figure 16), designed and built by Woods Hole Oceanographic Institution (WHOI) with the support of SSC Pacific,[21,22] will provide a new level of access for deep ocean research down to 11,000 meters. Two different operational modes are possible with Nereus: autonomous or remotely operated. For broad area survey, the vehicle can operate untethered as an autonomous underwater vehicle (AUV), capable of exploring and mapping the seafloor with sonars, cameras, and other on-board sensors. For detailed imaging and sampling, Nereus can be converted at sea to become a remotely operated vehicle (ROV). The ROV configuration incorporates a lightweight fiber-optic tether to the surface for high-bandwidth real-time video and data telemetry to the surface, enabling high-quality teleoperation, manipulation and sampling. Funding for the development of the Nereus vehicle and its fiber management system has been made available by the National Science Foundation, Office of Naval Research, and the National Oceanic and Atmospheric Administration.

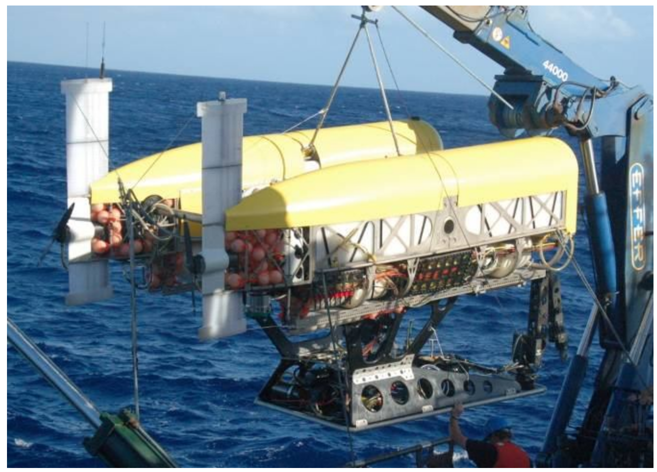

Figure 16. Nereus in the ROV Configuration.

SSC Pacific developed the fiber tether system over a 4-year period, supported by both simulation and extensive field testing with WHOI. Initial tests in November 2004 demonstrated the feasibility of using a light fiber optic cable in a vertical deployment. Tests in December 2005 demonstrated the utility of the buffered fiber operating on an underwater vehicle, using the WHOI ABE autonomous vehicle as a proxy for the future HROV. Based on data from the two fiber trials, a robust cable-deployment system was designed for the buffered fiber, accommodating its breaking strength of approximately 4 kilograms. The design is based on using a sub-surface depressor as a transition point from a reinforced cable to the light fiber, thus protecting the delicate fiber from the near-surface high energy environment. In this design, a fiber spool assembly is mounted within the depressor, paying out fiber at a pre-set tension with the motion of the depressor. An identical spool assembly is mounted to the vehicle, paying out fiber with the motion of the vehicle. A prototype of this system was built and tested in May 2006. The cable-deployment system was integrated with the actual Nereus vehicle in Fall 2007. Initial sea trials were conducted near Hawaii in November 2007. Operational procedures for launch and recovery were developed and tested. Four dives were made in the ROV configuration using the fiber, culminating in a 4.5-hour dive to 2267 meters. During all ROV dives, the fiber remained intact until purposely cut. After additional testing and integration, deep sea testing is planned in the Marianna Trench in May 2009.

4.3 Mine Countermeasures UUVs

SSC Pacific provides support to the Program Management Office for Explosive Ordnance Disposal (EOD), PMS-408, in the outfitting of Fleet EOD Forces with unmanned underwater vehicles to meet operational requirements and mission needs for underwater mine countermeasures. In support of multiple acquisition programs, SSC Pacific provides technical and engineering services in development of specifications and requirements, hardware procurements and fabrication, product acceptance and engineering evaluations, development of tactics and Concept of Operations (CONOPS), training and introduction to Fleet personnel, technical support, and subsequent evaluations of effectiveness for outfitted systems. The UUVs are equipped with various navigational capabilities consisting of GPS, inertial, and acoustic navigation systems. The onboard sensors typically include video cameras, various sonars, current/temperature/density (CTD) sensors, and Acoustic Doppler Current Profilers (ADCPs). Missions supported include mine countermeasures in the very shallow water zone (approximately 3 to 12 meters), and in confined waterways such as channels, ports, and harbors (see Figure 17).

Additional projects are ongoing for outfitting Fleet forces with UUVs to search ship hulls for limpet mines or improvised explosive devices. With support from SSC Pacific, the Fleet now has initial capabilities to conduct search-classify-map missions and subsequent reacquire-identification missions. Additional work is ongoing for developing further capabilities and product improvements to the currently outfitted systems as new technologies are developed and readied for Fleet introduction.

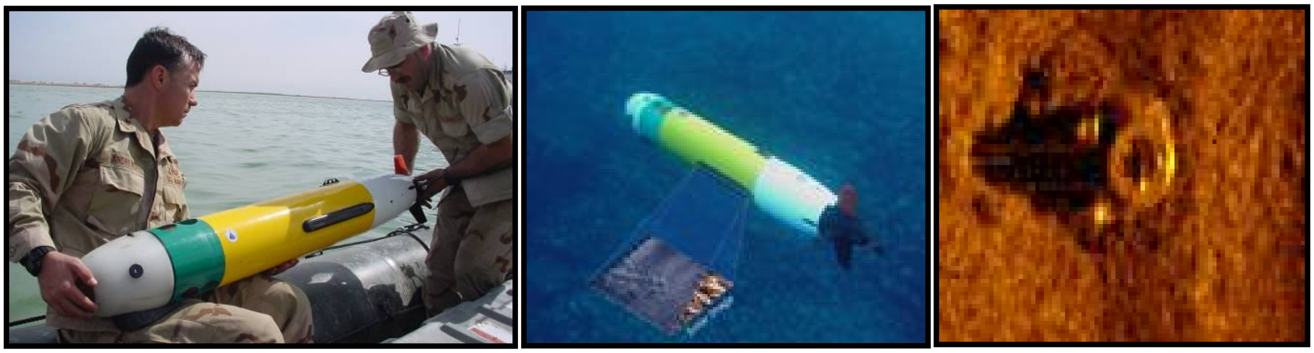

Figure 17. REMUS 100 UUV operated by Navy personnel and typical sonar imagery.

5. CONCLUSION

Unmanned systems activities at SSC Pacific span the entire spectrum, from research and development to product testing, fielding, and operational support, across all operational domains of ground, air, surface, and undersea. Our current research thrusts include: 1) robotic intelligence; 2) autonomous navigation on the sea surface, undersea, and in urban environments; 3) human presence detection; 4) 3-D world modeling; and 5) enhanced human-robot interaction.

Our technology-development efforts include: 1) increasing autonomy and operational range for man-portable UGVs; 2) developing a common operator control software architecture for a variety of heterogeneous unmanned vehicles; 3) demonstrating collaborative behaviors between UGVs and UAVs; and 4) providing improved capabilities for underwater countermine activities, ship hull inspection, and deep ocean exploration. Furthermore, we are supporting integration and post-production product-improvement activities in physical security and force protection domains, as well as providing RF communications expertise for the next-generation EOD robot design.

In addition to the above in-house activities, we also maintain a web site and a robot pool to support national research, development, experimentation, evaluation, training, and technology transfer. We are establishing an increasing number of Outreach Centers across the USA to better transition DoD results to the First Responder Community. Our goal is to contribute to the advancement of unmanned systems on several fronts while supporting the immediate and evolving needs of the warfighter.

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