Field operation of a robotic small waterplane area twin hull boat for shallow-water bathymetric characterization

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An innovative robotic boat has been developed for performing bathymetric mapping of very shallow coastal, estuarine, and inland waters. The boat uses a small waterplane area twin hull design to provide natural platform stability for a multibeam sonar payload, and a navigation system automatically guides the boat in a "lawn-mowing" pattern to map a region of interest. Developed in stages over five years as part of a low-cost student design program, the boat is now operational and is being used to generate science-quality maps for scientific and civil use; it is also being used as a testbed for evaluating the platform for other types of scientific missions and for demonstrating advanced control techniques. This paper reviews the student-based development process, describes the design of the boat, presents results from field operations, and reviews plans for future extensions to the system.

1. INTRODUCTION

Near-shore and inland waters play a critical role in society given their use for transportation, recreation, fishing, and filtering of anthropogenic by-products. Characterization and study of the terrain of these underwater regions, known as bathymetry, provides significant insight into their geologic history and future, erosion processes, local currents, suitability as marine habitats, the ability to accommodate activities such as boating, and the existence of man-made objects ranging from shipwrecks and debris to mines.

Early bathymetric studies were performed by using poles or weighted lines to estimate water depth directly under a boat (Bailey, 1953). In the 1930s, with an established understanding of basic acoustics and the speed of sound in water, echosounders began to be used, although these single beam devices were limited to measuring depth to within only 5 degrees of vertical (Urick, 1983). The era of modern bathymetry began in the 1970s with the advent of multibeam sonar systems, which use multiple acoustic beams and beam phase processing techniques to estimate the depth of broad swaths of the bottom terrain in a direction perpendicular to the direction of travel of the host vessel (Farr, 1980). Over the past four decades, this technology has matured, allowing dozens of beams to collectively illuminate swaths that are several times broader than the local water depth. Side-scan sonar systems use a modified architecture that specifically focuses energy in even wider cross-track swaths of area (Fish & Carr, 1991). For both multibeam and side-scan systems, sophisticated processing software has evolved, capable of stitching together sonar data into regional bathymetric maps with submeter resolution. Airborne LIDAR systems are also capable of generating bathymetric maps, although light absorption in water typically limits such systems to depths on the order of two to three times the Secci depth, which is often in the 10–15 m range (Irish & White, 1998).

Sonar instruments are often installed in the hulls or on poles mounted to the side of manned surface ships. It is also common to find these instruments installed on platforms towed by piloted ships. While these systems have been instrumental in mapping large regions of the ocean, the draft of the host vessels poses a danger to themselves and the environment in shallow, seminavigable waters, limiting the minimum depth of their measurements. As an example of this, a 2008–2009 NOAA bathymetric survey campaign to map Kachemak Bay, Alaska, was limited to depths greater than 20 m (Christie, 2010). While smaller vessels mitigate these issues, they are also more prone to wave disturbance due to large waterplane areas and the

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Figure 1. The Santa Clara University SWATH boat operating automatically during a bathymetric mission in Lake Tahoe, CA.

turbulence of shallow waters. The resulting pitch and roll disturbances complicate sonar data processing and induce errors in the reconstruction of maps. Underwater systems also exist for bathymetric applications. These include autonomous underwater vehicles (AUVs) such as the Monterey Bay Aquarium Research Institute's (MBARI) DORADO vehicle (Kirkwood, 2007) and the Kongsberg HUGIN (Hagen, Storkersen, Marthinsen, Sten, & Vestgard, 2008) AUV. These systems are also minimum-depth-limited to approximately 10 m. Airborne LIDAR systems are particularly well-suited to collecting shallow-water bathymetry; however, their high cost and limited availability make them an unrealistic option for many areas.

The robotic system described in this paper, shown in Figure 1 during a mapping mission in Lake Tahoe, CA, evolved from an interest in meeting the unique challenge of generating shallow-water bathymetry in a cost-effective manner. To meet the shallow-water challenge, a small waterplane area twin hull (SWATH) surface vessel was developed to provide a stable sensing platform. To lay the foundation for cost-effectiveness, robotic technology was used to automate key functions, allowing the boat to operate in both teleoperated and automated modes. The result was a low-cost robotic SWATH boat capable of conducting bathymetric operations for hours/day in an unattended mode and in water as shallow as 0.5 m. To the best of our knowledge, this unmanned SWATH system is the first of its kind to enter routine science field operations. This achievement required an understanding of the state-of-the-art in both the design of SWATH boats and of unmanned surface vessels (USVs), both of which are briefly reviewed here.

1.1. SWATH Boat Design Characteristics

SWATH boats employ a dual hull design with a minimal hull volume at the waterline. The effect of a small hull waterline is a minimal change in buoyancy due to wave interaction with the hull, resulting in a platform with excellent wave disturbance rejection and natural stability in pitch and roll (Dinsmore, 2004; Hart, 2000). SWATH boats have been shown to offer other advantages as well, such as enhanced deck space for equipment and the ability to maintain speed in high sea states (Nagai, 1987).

The original SWATH boat concept was patented in 1905 (Nelson, 1905). It was not until 1973, however, when the first SWATH boat, the U.S. Navy's SSP Kaimalino, was commissioned into service. Since that time, more than 50 SWATH boats have been built and placed into service for applications such as conducting oceanographic surveys (Gaul & McClure, 1984; Lang, Bishop, & Sturgeon, 1988), mine hunting and ordinance disposal (McCoy & Neely, 2000; Schaffer, Kupersmith, Wilson, & Valsi, 1991), and ferrying passengers (Chun, Kim, & Joo, 1997; Hart, 2000). About 80% of these ships are over 100 feet in length, and nearly all are longer than 40 feet (Dinsmore, 2004).

1.2. Unmanned Surface Vessels

USVs have the potential to reduce the risks and costs associated with marine operations ranging from military intervention to scientific characterization (Cornfield & Young, 2006; Curtin, Bellingham, Catipovic, & Webb, 1993). Military applications for USVs have been in place since World War II. During their first decades of use, such systems were generally controlled by a remote pilot and used as gunnery targets or mine countermeasure drones (Mine Warfare Forces, 2004). Over the past 15 years, the use of USVs has expanded to applications such as sweeping for mines, conducting scientific surveys, towing other marine assets, providing support functions for local underwater vehicles or instruments, and serving as technology research testbeds. Excellent reviews of the many USV systems that have been developed for such applications are provided in Bertram (2008), Manley (2008), and Caccia (2006).

Most USVs are under 15 m in length, and many use conventional hull designs that have been retrofitted for unmanned operation, such as standard monohull boats, rigid inflatable boats, jet skis, and kayaks. Some mine-sweeping, science, and testbed USVs use custom chasses resembling torpedoes and catamarans. State-of-the-practice technologies for enabling USV functions include the use of GPS for position sensing, automated waypoint navigation and path-following algorithms, and wireless communication links for remote piloting, supervisory control, and/or real-time streaming of mission data. Specific technologies of note include advanced vision systems for collision avoidance and navigation (Huntsberger, Aghazarian, Howard, & Trotz, 2011; Wolf et al., 2010), the CARACaS and MOOS-IvP autonomous control systems (Benjamin, Schmidt, Newman, & Leonard, 2010; Elkins, Sellers, & Monach, 2010), and the emergence of multi-USV systems (Curcio, Leonard, & Patrikalakis, 2005; Mahacek, Kitts, & Mas, 2012).

Of particular interest are USVs such as ACES (and its follow-on, AutoCAT), Springer, MESSIN, ROAZ, SESAMO, and DELFIM given their similarity to our own design. All of these are small USVs with lengths under 4 m and are capable of very shallow water operation on the order of 1 m depth. The first five use a catamaran design; MESSIN uses a SWATH design strategy similar to our own. All have been successfully operated in the marine environment. ACES, developed at MIT (Manley, 1997), Springer, developed at the University of Plymouth (Naeem, Xu, Sutton, & Chudley, 2006), ROAZ, developed by the Instituto Superior de Engenharia do Porto (Martins et al., 2007), and MESSIN, developed by the University of Rostock (Majohr, Buch, & Korte, 2000), were all originally developed to conduct shallow water environmental surveys. SESAMO was developed by the Consiglio Nazionale delle Richerche Istituto di Studi sui sistemi Intelligenti per l'Automazione in Italy for studies of the air-sea interface (Caccia et al., 2005). DELFIM was developed by the Lisbon Dynamical System and Ocean Robotics Laboratory (Alves et al., 2006) to work cooperatively with an autonomous underwater robot. Recent literature suggests that these systems are now either nonoperational or serve primarily as navigation research testbeds (Almeida et al., 2009; Bibuli, Bruzzone, Caccia, & Lapierre, 2009; Majohr & Buch, 2006; Naeem, Xu, Sutton, & Tiano, 2008; Pascoal, Silvestre, & Oliveira, 2006).

2. BOAT DEVELOPMENT

The robotic SWATH boat was developed as part of an active field robotics program within the Santa Clara University (SCU) Robotic Systems Laboratory (RSL). RSL conducts an integrative research and education program in intelligent robotic systems. Undergraduate students routinely develop a wide range of robots, and their field control systems, for operation in land, sea, air, and space (Kitts, 2003). Graduate students inject the results of their own technology development research to provide functions with a significant level of sophistication. The robotic systems are developed and operated in support of specific scientific and technology validation missions. RSL routinely works with a wide variety of sponsors and collaborators in government (NSF, NASA, NOAA, USGS, U.S. Navy, U.S. Air Force, and so on), industry (Lockheed, BMW, ACRi, and so on), academia (UT Austin, Stanford, UC Santa Cruz, and so on), and the nonprofit sector (California Space Grant, MBARI, IEEE, and so on).

Development of the SWATH boat relied on a strong collaboration between RSL, MBARI, and the University of Alaska at Fairbanks (UAF), which hosts NOAA's West Coast and Polar Regions Undersea Research Center (WC&PRURC). Prior to the boat's development, these organizations had worked together to develop a marine-oriented element within the RSL field robotics program (Kitts, Kirkwood, & Wheat, 2010), with a focus primarily on the development and operation of several student-built tethered remotely operated vehicles (ROVs).

The SWATH development program was conceived with an interest in developing a stable instrumentation platform for inland lakes, estuaries, and coastal waters in conditions up to a sea state of 2. Its concept of operations called for automated operations for up to eight hours in uncluttered waters with on-call operators available to initiate and terminate deployment activities and to also be available to intervene in anomalous conditions. To explore this concept, the team decided to develop a small-scale, low-cost demonstration vehicle capable of performing science and also serving as a testbed for technologies and control strategies that would be essential to a larger-scale system.

Development of this small-scale demonstration vehicle was initiated in 2005 as part of an interdisciplinary undergraduate capstone project. This first team focused on the SWATH hull design, and characterization of this hull continued as part of a MBARI summer intern project. Several follow-on SCU capstone projects and MBARI summer internships were conducted over the following three years to bring the system to a level capable of performing science operations (Beck et al., 2009). Overall, students were completely responsible for the design, development, fabrication, and test of the system, although strong mentoring and routine industry design reviews certainly played a critical role in ensuring project success. A student-based development team helped to achieve a low-cost project. In addition, apart from payload instruments, the cost of boat components totals less than $5,000. The current science-quality bathymetric mapping instrument suite is valued on the order of $50,000.

The current boat is now capable of automatically supporting science operations for hours at a time; however, in deployments to date, a student operations team has always

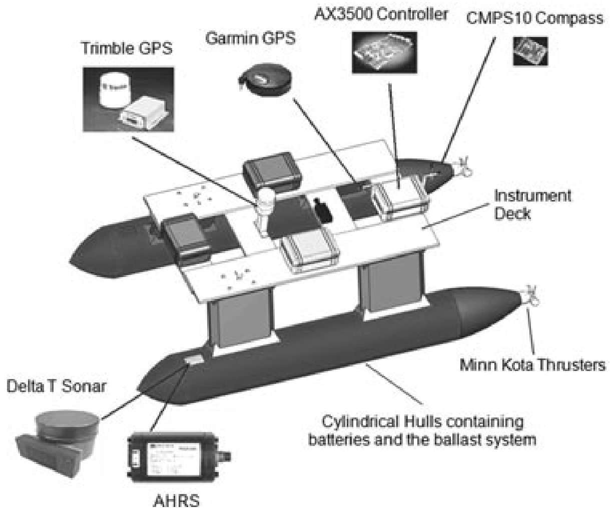


Figure 2. The SWATH boat mechanical configuration and component locations. Instruments are mounted either in submerged pontoons or on the above-water instrument platform. The boat operates with the waterline along the struts of the hull, thereby reducing pitch/roll disturbances due to waves.

been on-site to ensure safety, to respond to problems, and to interactively explore new system capabilities as part of the RSL engineering research program.

3. SYSTEM DESIGN

The operational SWATH system includes the boat and its onboard components as well as an offboard control station. Onboard components are segmented into modular, standalone payload and platform subsystems such that payloads can be easily swapped. This strategy provides many operational and logistical advantages but results in the need to duplicate some functions (such as position and orientation sensing) across the platform and payload portions of the system.

An offboard control station communicates with the payload and platform subsystems separately. The control station supports a range of operator interaction from remote piloting to supervisory control. Station software can archive data and stream them to remote applications if Internet connectivity is available. For the bathymetry missions discussed in this paper, the MBARI mapping software, MB System, is used postmission to filter payload instrument data and generate bathymetric maps (Caress & Chayes, 2010). Figure 2 presents an annotated diagram of the SWATH boat and its components.

3.1. SWATH Hull

A SWATH design was selected due to its platform stability characteristics as well as an academic interest in the viability of this hull type for small, automated surface craft. Platform stability was essential for instrumentation-driven demands such as minimizing unwanted pitch and roll for sonar and reducing stress-inducing heave for tethered instrument packages.

This design was implemented by using two PVC cylindrical hulls, each joined to the aluminum honeycomb platform by two struts. After a series of stability tests over a range of strut angle, an angle of 20° per strut was selected (Mahacek, 2005). Each strut is encased in fiberglass-covered polyurethane buoyancy packs to ensure the minimal wave response required to prevent the platform from becoming submerged in high sea states. Hull rigidity is improved by using stainless steel cross bracings between each strut and the opposite side of the platform. Overall, the hull is 3.4 m in length, 1.3 m tall and wide, and 360 kg.

Functional components are installed both in the underwater pontoons as well as on the main deck of the boat. The pontoons hold components that must be submerged, such as the thrusters and some science instruments; batteries, installed in watertight containers, are also located in the pontoons to lower the boat's center of mass. The pontoons also contain the buoyancy system, which includes static foam packs as well as an adjustable system that uses air tanks at each end of both pontoons. These tanks are filled manually with an external pump to level and set the nominal freeboard for the boat at the start of a mission.

3.2. Boat Components

Figure 3 shows a block diagram of boat components, to include the boat's payload, propulsion, communication, and control equipment. Propulsion is provided by two Minn Kota RT55 electric trolling motors, each providing up to 55 pounds of thrust, that are installed at the aft end of each hull pontoon. This mechanical configuration allows the boat to be controlled via a differential drive strategy. The motors use a RoboteQ AX3500 brushed dc motor amplifier. These components take boat-level drive commands from an onboard computer and convert these to drive signals for each individual thruster.

Communication between the boat and its offboard control station is supported through several wireless links. A short-range 100 Mbps wireless LAN connection is used to monitor science computer operation, allowing operators to ensure that payload equipment is properly operating prior to departing on a science mission. A long-range analog video transmitter allows operators to have an onboard view of the boat's local environment via an onboard camera. In addition, a long-range 19,200 kbps serial radiomodem is used to relay boat navigation and control information. Finally, additional wireless links are occasionally added to perform modular tests of new subsystems prior to their integration with the boat's overall control system; the boat's canard and winch subsystems currently use such wireless links, operating at 9,600 baud.

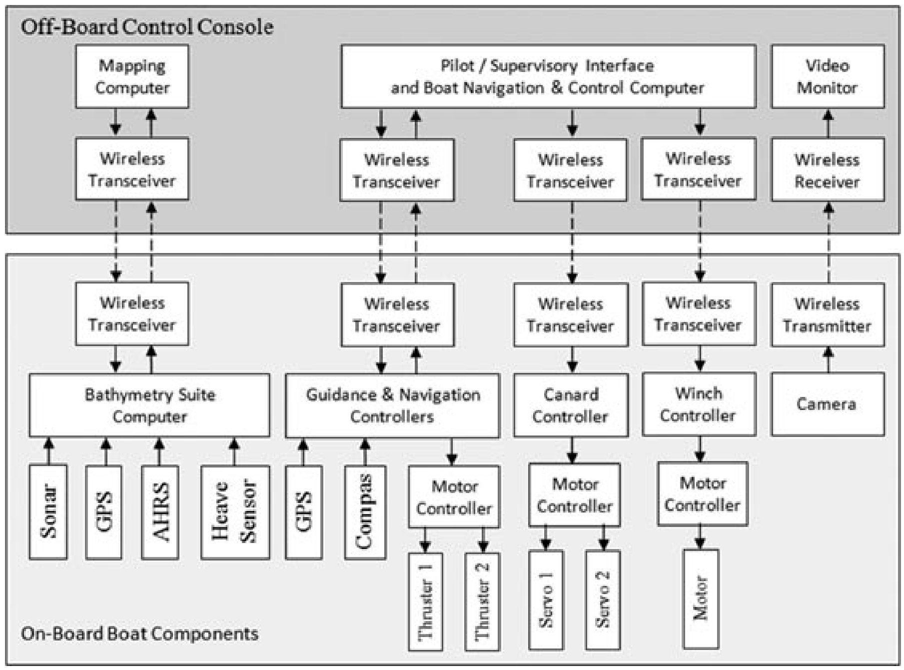


Figure 3. Component block diagram for primary boat components. Several functional suites of equipment operate in parallel, thereby balancing operational functionality with modularity appropriate for a student-based development project.

Navigation components support both piloted and automated navigation. Position data are provided by a low-cost Garmin 18 GPS sensor with a 5 Hz update rate and a rated absolute error of ±3 m rms. A Deventech CMPS10 compass with a rated error of ±3° and a 10 Hz update rate provides orientation data. The boat has two onboard BasicX-24 embedded controllers, each of which uses an 8-bit RISC ATMEGA8535 processor and has 32 KB of EEPROM and 400 bytes of RAM. These processors execute a multitasking version of the BASIC programming language and are capable of executing 83,000 lines of code per second. Although onboard computers are capable of implementing navigation control, these functions are currently being implemented on the offboard computer to support interactive testing of new navigation controllers during science operations. Given this, position data are acquired by the onboard controllers and wirelessly routed to the offboard control computer where drive commands are generated. These drive commands are wirelessly relayed back to the boat and routed by the onboard controllers to the motor driver board for execution. A more detailed description of the design and performance of the navigation algorithm is provided later.

The boat also includes a pair of differentially articulating canards. Mounted on the front of the boat, these control surfaces provide hydrodynamic torques to maintain level operation. This system currently does not have the speed of response to address wave-generated disturbances. Instead, its primary use is to provide pitch-trimming capability to compensate for the boat pitching forward as its speed is increased due to the boat's natural hydrodynamic properties; this trimming can be done via remote command or set manually. By using the canards to compensate for pitch errors, the boat can be operated at higher speeds, thereby enhancing the rate at which mapping operations can be conducted. The canards are also manually positioned for a nose up pose when the boat is towed, which is often done to accelerate its deployment to offshore mapping regions.

A small winch is available to mount on the boat and is used to lower an instrument package into the water. Currently, a Seabird CTD sensor is available for such use and operates in a data-logging mode. The winch/CTD subsystem is used for volumetric sampling of bodies of water and does not directly support the bathymetric mapping operation of the boat.

Six 12 V, 84 Amp-hr sealed lead-acid batteries provide boat power in the form of both 12 and 24 V power supplies. This power capacity is capable of powering all boat systems at full duty cycle for more than 8 h, thereby satisfying design requirements.

3.3. Instrumentation

The bathymetry payload consists of a science computer that logs data from multiple instruments. The primary instrument is an Imagenix 837 "Delta T" multibeam imaging

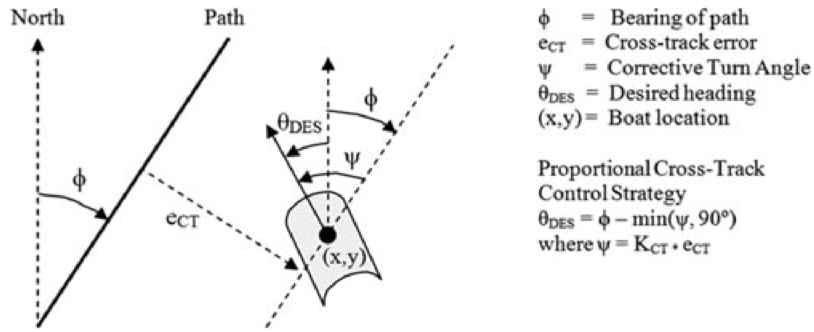


Figure 4. Cross-track control strategy. The cross-track controller computes a desired heading for the boat that is provided to an inner loop heading controller. The cross-track control strategy adds a corrective turn to a default heading that matches the bearing of the current path segment. The angle of the corrective turn is a PID function of the cross-track error and is limited to 90° such that the boat sails toward the path in a perpendicular manner for large cross-track deviations.

sonar, which is capable of producing 20 imaging frames per second for depths of up to 100 m. Additional sensors include a high-precision marine-grade Trimble GPS unit, a Crossbow Attitude Heading Reference Sensor, and a Teledyne heave sensor. This equipment is installed in the subsea pontoons or in a dedicated enclosure mounted on the main boat platform.

The boat also supports a secondary payload in the form of a Seabird CTD that can be hull mounted or deployed to different depths via a small winch mounted on the main deck.

4. NAVIGATION AND CONTROL

The boat's location and heading are provided by Garmin GPS and Devantech compass components. The boat's navigation and control system is capable of achieving its performance requirements without the need of filters to process these position and orientation data.

The boat has automated control functions supporting heading control, waypoint control, and path control. Although trajectory control (in which the boat is controlled both to be on a specific path and to be at a specific point along that path at a specific time) has been demonstrated in the past, this is generally not used for bathymetric operations; the reason for this is explained later in this article. Finally, a piloted mode is available for direct vehicle-level control of the boat based either on the pilot's line-of-sight view of the boat or on the image from the onboard camera.

For mapping operations, the boat operates in a path-following mode, which is implemented using constant forward thrust and differential torque compensation to eliminate cross-track errors. Figure 4 graphically presents the cross-track control strategy, and Figure 5 shows a block diagram depicting the structure of this control mode. Cross-track error, the distance the boat is from its desired path, is computed based on the boat's reported GPS position and a representation of the path; for a straight line path segment, this representation consists of the segment end points and the direction of travel along the segment. The cross-track controller feeds a desired heading command to an inner loop boat heading controller, which uses a simple

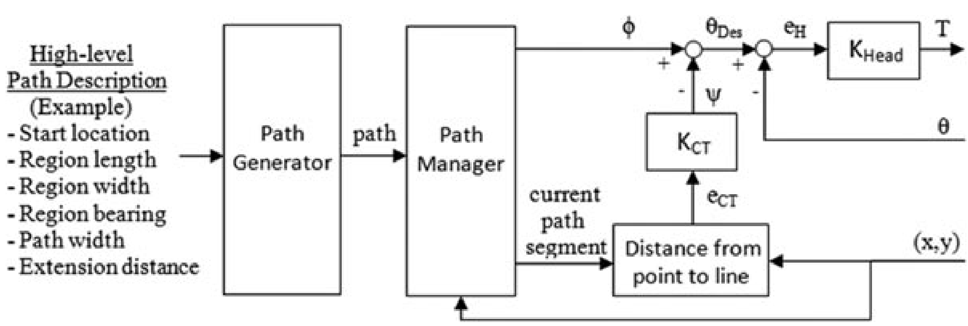


Figure 5. Cross-track control architecture used during mapping operations. The cross-track controller provides a desired heading to an inner loop heading controller, which uses a simple linear control function. A path manager function manages the current path segment, and a path generator computes a complete multisegment path based on a high-level specification of the map to be generated.

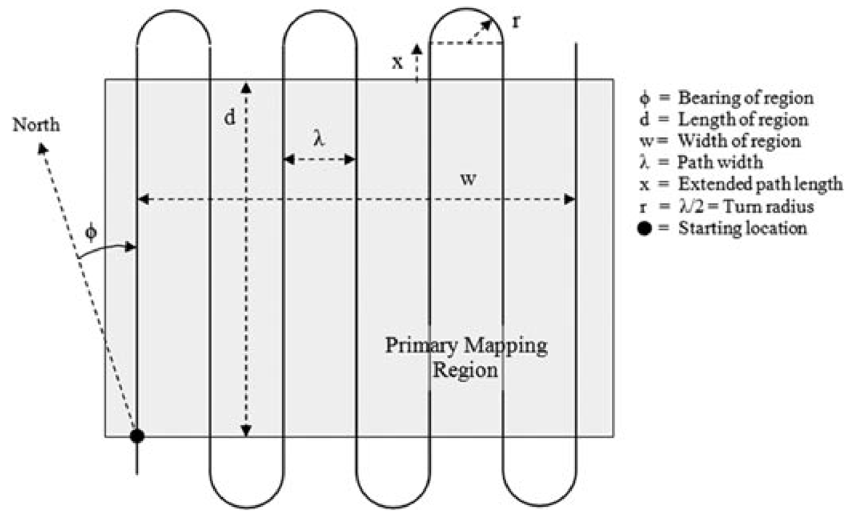


Figure 6. Example of a mow-the-lawn path for mapping operations. A path is composed of straight line segments through the region of interest. Paths extend beyond the region and are connected by semicircular segments. Path spacing is based on depth, sonar beamwidth, and the desired amount of mapping overlap.

proportional control law. In general, the cross-track control strategy specifies a desired heading that matches the path bearing plus or minus a corrective heading term based on the cross-track error; the corrective heading term is limited to 90 degrees such that the boat heads toward the path in a perpendicular fashion for very large cross-track deviations. To date, this corrective term has been limited to simple, linear Proportional-Integral-Derivative (PID) functions of the cross-track error given that these have been capable of satisfying design objectives. The control system servo rate is approximately 5 Hz.

For automated bathymetric mapping, a "mow-the-lawn" strategy is used, with a desired path that consists of a series of parallel line segments that span the region of interest. The spacing between these lines is a function of depth, sonar beamwidth, and the amount of beam overlap desired (50–75% overlap is typical). Line segments extend beyond the region of interest (to allow transient cross-track errors from turning to die out) and are connected by semicircular arcs. When navigating along these arcs, the path controller corrects cross-track error with respect to a line tangent to the point on the arc that is closest to the boat. Figure 6 shows an example of such a path. As shown in Figure 5, a path manager function manages the process of incrementing the current path segment over time and of passing a representation of the current path segment to the vehicle torque controller.

A path generation function is capable of deriving the overall path (composed of a sequence of path segments) from a high-level specification of a rectangular targeted mapping region. For example, the mapping region can be specified by the location of a corner of the region and the length, width, and orientation of the region. Additional parameters for the path spacing (for which a default policy exists) and the length that the straight line segments should extend beyond the mapping region are also specified. Functions exist to change the direction of travel along a created path and to geometrically flip and/or mirror a path. The paths can also be adapted in real time to terminate a session or modify the extent of the remaining map region.

For an arbitrary region that must be mapped, the operations team typically obtains a rough estimate of depth throughout the region either from existing bathymetry, from point measurements made by a single beam sonar from a manned support boat, or by running several sparse mapping sessions throughout the area. Given general knowledge about a region's depth profile and formations such as ridges and slopes, the team manually divides the region into rectangular subregions; subregions are mapped in individual sessions, with the regional map created through a mosaicing function available through the MB System processing software. In general, subregions are selected to span a limited range of depth such that the path spacing and sonar gain settings are appropriate over the entire subregion.

Path planning, real-time control, and performance monitoring are implemented through a student-developed software architecture, shown in Figure 7. All significant computational tasks are performed on the offboard control workstation, with onboard microcontrollers responsible for relaying sensor data to the offboard controller and routing boat drive commands to the onboard motor controller. More specifically, planning and control functions are programmed in the Matlab/Simulink

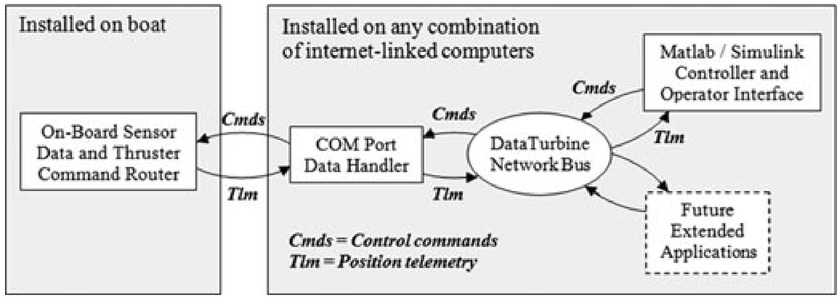


Figure 7. Distributed software architecture for the boat control system. Planning and control are implemented in the Matlab/Simulink environment. Boat drive commands and sensor data are routed to/from the boat via the DataTurbine data server, a serial port gateway application, a wireless link, and routing software on the onboard boat microcontrollers. The DataTurbine routes data using a channel subscription model and makes it easy to integrate future applications that can execute on any networked computer.

environment, which executes in its interpreted mode during real-time operations. A streaming data server, known as the DataTurbine (Fountain, Tilak, Hubbard, Shin, & Freudinger, 2007), routes commands and telemetry between the Matlab/Simulink environment and a simple application that handles communication with the boat via a serial port connection to the wireless communication system. This server uses a channel subscription model that treats applications as data sources and sinks and allows multiple sink applications, written in diverse languages and executing on any networked computer, to access data provided by any source application. Embedded software executing on the boat's microcontrollers routes drive commands to the boat's motor controller and relays navigation sensor data back to the offboard computer; given the use of BasicX microcontrollers, this software is written in a multitasking version of the BASIC programming language.

There are several reasons why this particular motion control software architecture was adopted. First, as opposed to using an existing system such as MOOS, there was great student interest in developing a custom control architecture; given the expertise and focus of the hosting research lab, this approach was deemed appropriate and manageable. Second, while the execution of Matlab/Simulink in its interactive mode is slow by typical real-time control standards, this mode is fast enough for control of the boat system; furthermore, it allows for simple and direct real-time adaptation and editing of planning and control functions/parameters, which is a desired system attribute given the role of the system as an education and research testbed. Matlab/Simulink is also the central software tool used in the SCU robotics program such that its use ensures that all students in the program will have an appropriate level of familiarity with the system. Third, while the DataTurbine may seem like an unnecessary level of middleware, it allows for simple and flexible expansion of the system's software architecture in the future given the ability to easily exchange data between a wide range of distributed applications through the channel subscription process. Finally, the combination of Matlab/Simulink with the DataTurbine is a central part of several other operational robotic systems within the SCU robotics program, ranging from a command and control network for NASA spacecraft (Kitts et al., 2008) to an operational multiboat system (Mahacek et al., 2012). The reuse of this software architecture is critical in supporting the wide range of projects conducted in the program; indeed, many of the boat's hardware components, such as the motor controller, embedded controllers, and navigation sensors, were selected largely due to their use in other robotic systems in the program.

Figure 8 summarizes navigation performance for a typical mission. Figure 8(a) shows the prescribed path in blue and the actual boat path in red; the green region is the area to be mapped. The objective is to minimize cross-track errors along the straight paths when the boat is in the green region; higher errors outside of this region are acceptable as the boat turns from one path to another. Figure 8(b) shows the cross-track error of the boat over time; the green portion of this time history highlights the error in the mapping region. The rms error in the mapping region for this particular operation was 0.534 m; this is a precision metric rather than a measurement of absolute accuracy, which is sufficient for ensuring coverage of the region such that areas are not missed. Table I provides the cross-track rms error for several other mapping sessions performed over the past year at locations throughout California; as is seen, rms error is routinely under 1 m for relatively calm conditions.

5. MAPPING PERFORMANCE

To generate maps, the individual time-referenced logs of each instrument in the bathymetric payload suite are merged into a single file that can be ingested by the MB System software package. This suite provides a variety of data analysis, editing, and visualization routines that are

Table I. Cross-track control performance during several mapping deployments.

Session	Location	Conditions	rms Error (m)	Map Dimensions (m × m)	Path Width (m)
1	Emerald Bay, Lake Tahoe	Breeze, ~3 knots Current < 1 knot	0.74	430 × 100	20
2	Del Valle Reservoir	Breeze, ~3 knots Current < 1 knot	0.60	70 × 80	20
3	Stevens Creek Reservoir 1	Calm wind, < 1 knot Current < 1 knot	0.56	90 × 80	20
4	Stevens Creek Reservoir 2	Calm wind, < 1 knot Current < 1 knot	0.63	90 × 80	20
5	Stevens Creek Reservoir 3	Calm wind, < 1 knot Current < 1 knot	0.40	120 × 120	20
6	Stevens Creek Reservoir 4	Calm wind, < 1 knot Current < 1 knot	0.51	90 × 50	10
7	Stevens Creek Reservoir 5	Calm wind, < 1 knot Current < 1 knot	0.53	60 × 90	20

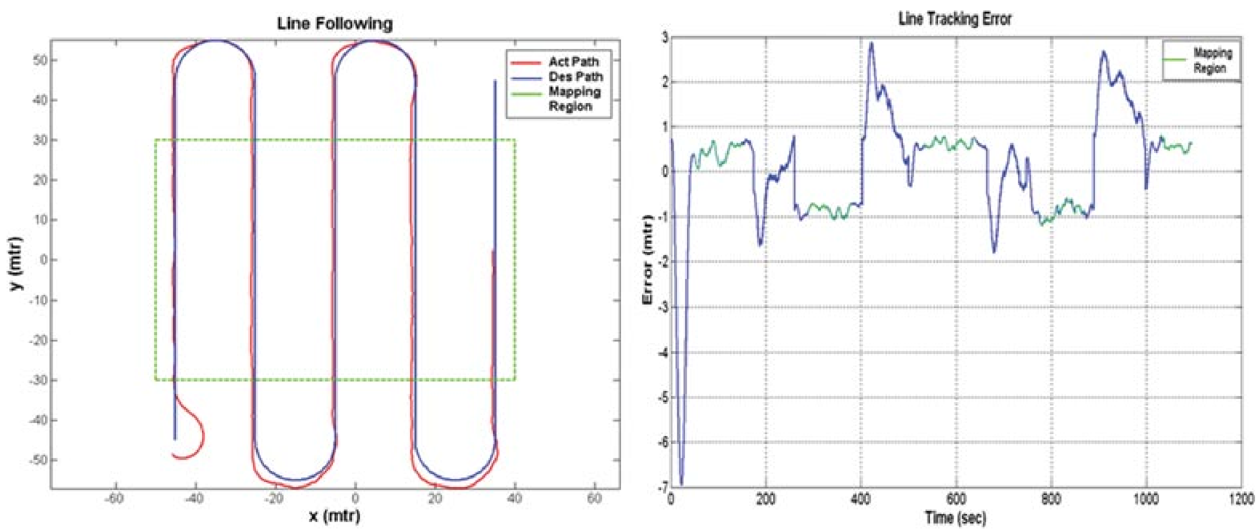
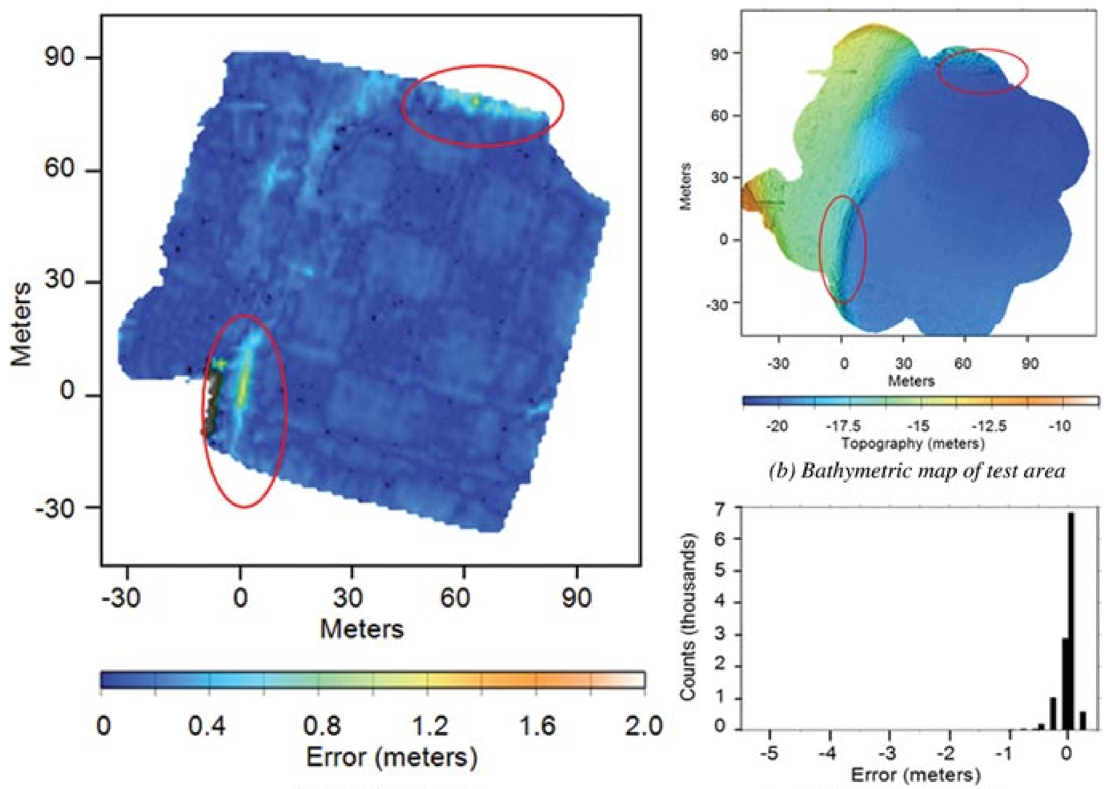


Figure 8. Navigation performance of the SWATH boat during automated "mow-the-lawn" mapping operations. (a) Overhead view of mapping region showing the area to be mapped (in green), the desired path (in blue), and the actual boat path (in red). (b) Time history of cross-track error during the mapping operation shown in part (a). The errors in green are when the boat is in the mapping region.

commonly used in the generation of science-class bathymetric maps.

To characterize mapping precision, a standard bathymetric repeatability analysis used by MBARI (Caress et al., 2007) was performed. In this test, a region is mapped twice with different track headings, and the spatial difference in depth estimates between the two maps is analyzed. As an example of this, Figure 9 shows the results for a test region in Stevens Creek Reservoir in Cupertino, CA, at a depth of approximately 20 m, at a nominal mapping speed of 1.6 km/h, and with ideal mapping conditions (no wind, no waves, and no current). Figure 9(a) shows the error map for this exercise, displaying the depth differences at each point over the spatial test area. Figure 9(b) shows one of the original maps of this region. Figure 9(c) shows a frequency histogram of the errors. The histogram leads to an estimate of 0.268 m bathymetric repeatability at the one standard deviation level, for the given depth and operating conditions. It is interesting to note that the largest excursions in repeatability occur at the locations with the highest depth gradients, with these areas circled in red in the figures; this correlation is expected and is driven primarily by limitations on boat position knowledge.

As a measure of performance, bathymetric repeatability is typically stated as a percentage of depth. For the analysis shown in Figure 9, this leads to a repeatability of approximately 1.4% of depth at the one standard deviation level. This is an outstanding result given that scientific bathymetric operations are often conducted with a repeatability on the order of 5% of depth. The results certainly benefited from the ideal environmental conditions, but they also indicate the quality level that can be achieved with the system. In addition, given the team's ability to conduct this analysis, future field deployments can duplicate a



(a) Difference plot *(c) Histogram of map differences*

Figure 9. Results of a precision test. In (a), the error map is shown. This map is the difference in depths of two independently created maps across the spatial region of interest. A subtle patchwork pattern can also be seen in the error map, indicating the existence of a roll bias that still has yet to be filtered out; additional filtering will lead to reduced error. In (b), the mapped area is shown. It is worth noting that the lines of elevated error seen in (a) correspond to locations where the depth changes most rapidly, as can be seen in (b). In (c) a histogram of topographic differences between these deployments is provided; the standard deviation of these errors is approximately 0.268 m.

repeatability analysis for the operating conditions at that time to provide a customized quality assessment of the maps created during that operation.

6. FIELD MISSIONS

The SWATH boat entered science operations in the fall of 2009, with an initial deployment in Lake Tahoe, CA. Since that time, it has been used to perform additional mapping operations in Lake Tahoe and in Stevens Creek Reservoir in Cupertino, CA; these operations have been in support of several collaborating scientists as well as for a number of governmental agencies. The system has also been operated extensively for development and test purposes at locations throughout northern California, to include Elkhorn Slough in Moss Landing, San Francisco Bay, and a number of additional lakes, reservoirs, and estuaries.

For its fall 2009 science deployment in Lake Tahoe, CA, the RSL student team worked with marine geologists from the USGS and the University of Nevada, Reno (UNR). The RSL team had previously worked with the same group of geologists in a series of annual science missions in Lake Tahoe, using RSL's Triton ROV, to study a wide range of underwater geologic features. One of the most interesting studies occurred during dives in 2005 when evidence of tsunami waves was found in the form of large-scale boulder ridges along the Tahoe Shelf at the north end of the lake (Moore, Schweickert, Robinson, Lahren, & Kitts, 2006). During these dives, visual images and physical samples were collected. A clear desire of the science team was to have high-resolution bathymetry of these ridges.

Although this desire was not a prime motivator for development of the SWATH boat, it was clear that the system would be capable of achieving the scientific objectives of the USGS/UNR team. So, in October 2009, the SWATH boat was deployed along Lake Tahoe's northern shelf for its first science deployment. The objective of this deployment was to create a map along one of the ROV paths that

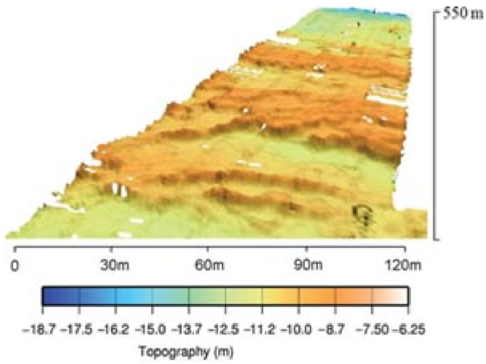


Figure 10. Mapping results from the fall 2009 Lake Tahoe mission. This perspective view of a portion of the map shows the detailed boulder ridge features, discovered during a previous SCU/USGS underwater robot mission. White spaces in the map indicate points at which no valid mapping data exist; this map was produced during the team's first scientific deployment, before more conservative operational parameters regarding speed and track spacing were adopted to prevent such data loss. The vertical scale of the map has been exaggerated to accentuate the topographic features of interest.

had been flown in 2006 to map a section of the boulder ridges. Figure 10 shows a perspective view of a portion of the area that was mapped. Average depths are consistent with lower-resolution USGS LIDAR bathymetry collected in 2000. Furthermore, the map clearly shows the boulder ridge features that are of scientific interest but are not apparent in the 2000 USGS map. This mapping data provided the USGS/UNR science team with large-scale morphological information regarding the structure of the ridges.

As a second example of the SWATH boat at work, Figure 11 shows a map of Stevens Creek Reservoir, which is being created for the Santa Clara County Parks Office. This composite map was generated based on multiple deployments during the summer and fall of 2011. The map clearly shows the tiered, man-made structure of this body of water. This reservoir is the site of a significant amount of engineering test operations for the boat, to include the navigation and mapping repeatability tests presented earlier.

As a final example of mapping operations, Figure 12 presents bathymetry of portions of Emerald Bay in Lake Tahoe, CA, created during a multiday mission during September 2011. This particular map was created to identify geologically interesting features in the bay, such as a ridge that extends across the northern portion of the bay to Fannette Island, landslide tailings, and other features. The existence and location of such features are of interest to collaborating scientists studying the bay's morphology and the activity of fault lines. In addition to serving as a scientific data product, the map was also used to identify features that were then visually explored through the use

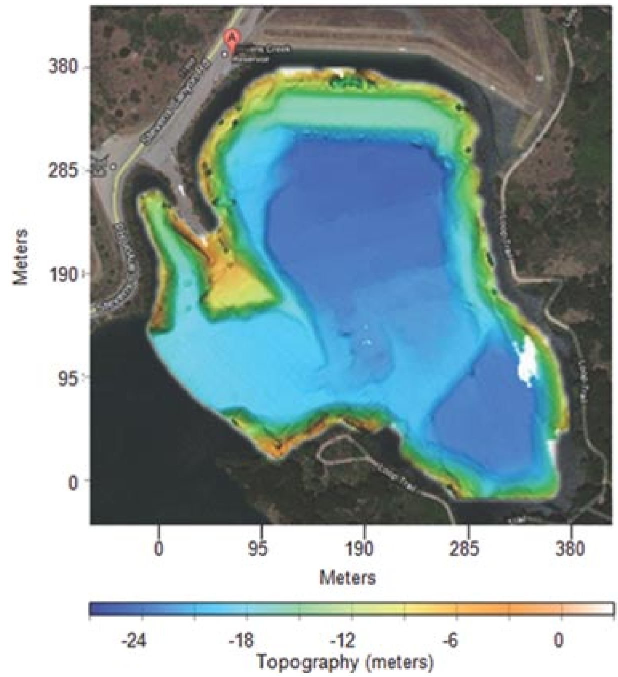


Figure 11. Bathymetric map of a portion of Stevens Creek Reservoir in Cupertino, CA, created during a summer 2011 mapping campaign. The map is shown here overlaid on an overhead photo of the area, available on Google Maps.

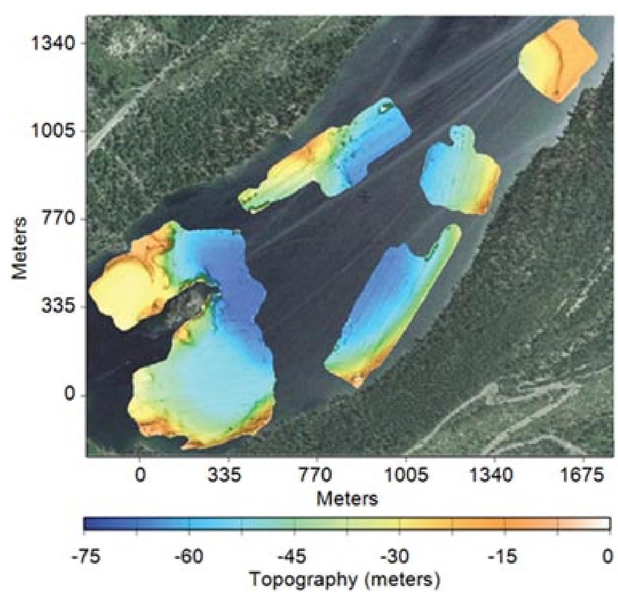


Figure 12. Bathymetric map of portions of Emerald Bay in Lake Tahoe, CA, created during a September 2011 mapping mission. The map is shown here overlaid on an overhead photo of the area, available on Google Maps.

Table II. Physical specifications for the SWATH boat.

Length	3.4 m
Width	1.3 m
Height	1.3 m
Weight	360 kg

Table III. Typical operational specifications for the SWATH boat.

Mapping speed	1.6 km/h
Mapping coverage	0.05 km^2/h @ 25 m depth
Operating duration	8 h at full power 11+ h for typical operating conditions
Wireless range	300 m

of one of Santa Clara's underwater robots during the same mission.

During scientific mapping operations, conservative operating procedures generally specify an operating speed of 1.6 km/h, and a cross-track spacing that is approximately 25% larger than the average local depth; this ensures a mapping overlap of 75%, thereby preventing unmapped portions of the area of interest given navigation errors and pitch/roll biases. For example, when mapping an area with an average depth of 25 m, this leads to a mapping coverage rate of approximately 0.05 km^2/h. Tables II and III summarize the primary physical and typical operational specifications for the boat.

7. LESSONS LEARNED

The development and operational use of the SWATH boat offers several lessons of general interest. First and foremost is the suitability of a SWATH platform for operation in shallow, protected waters. In these environments, the platform demonstrates passive pitch and roll disturbance rejection that enhances the boat's utility as a platform for bathymetric mapping. This boat is one of the few known SWATH designs under 12 feet in length; given constraints on the operational sea state, the benefits of the SWATH design appear to scale well at this size.

A second lesson pertains to the robustness of low-cost components for use in a complex robotic system that must operate automatically for hours at a time in a field environment. Most of the individual sensing, communication, and computing components in the boat's navigation and control system cost under $100 and are readily available to and used by students and hobby-level enthusiasts. These components are easy to use and integrate, and they have been integrated into the system to meet performance requirements and withstand the demands of the operational environment.

The third lesson pertains to the use of path control rather than trajectory control as the most appropriate control strategy during mapping operations. In early tests, it was found that controlling the boat to a specific point on the desired path at a given time caused undesirable variations in forward speed, sometimes leading to forward speeds great enough to cause gaps in sonar coverage. Ultimately, it was decided that smooth, limited forward velocity was a greater requirement than maintaining any desired longitudinal position along the path. For this reason, during mapping operations, a constant forward thrust is used along with a closed-loop cross-track controller.

A final lesson reaffirms a finding that has been learned on other student-based projects within the Santa Clara robotics program. This finding is that it is possible to conduct a student-based education and research program that is capable of producing and operating complex, professional-class, science-capable robotic systems at low cost. In the Santa Clara program, similar success has been achieved in the development and operation of underwater robots and in the command and control of NASA spacecraft (Kitts et al., 2010, 2008). As experienced in the SWATH program, these projects often start on shoestring budgets of only a few thousand dollars per year and with teams of undergraduate students working on the program for course credit. Over successive years and teams, capability is extended until such time as the system can be demonstrated in an operational setting. Upon successful demonstration, one or more initial sponsors are typically identified to perform initial field operations, with financial support typically covering operational costs for travel and direct deployment-related costs. As the capabilities of the system are matured over time and as the student team demonstrates the ability to reliably operate the system in the field to produce quality results, the cadre of investigators and users is expanded, and additional financial resources are found to support student interns and improved instrumentation. These projects often benefit through the involvement of graduate level research students who provide long-term continuity for the project and who are able to use the robotic system as an experimental testbed for their own research.

8. ONGOING AND FUTURE WORK

The SCU SWATH boat is now a fully operational bathymetric mapping system. The system is currently being operated by students on the order of 30 days/year to support scientific and civil map-making as well as student education. Over the next several years, local inland operations will continue with the USGS, the Park Service, and academic scientists for operations throughout Lake Tahoe, with MBARI for operations in Elkhorn Slough in Moss Landing, CA, and with the County Parks Office for civil management of additional reservoirs and lakes in Santa Clara County, CA. The team is also exploring a series of more challenging deployments with NOAA and MBARI for surveying portions of Monterey Bay, CA, around Puget Sound, WA, and in Kasitsna Bay, AK. Ultimately, the team plans to manage operations such that the boat would be capable of rapidly responding to transient science events (for characterizing phenomena such as algae blooms) and to disasters (for characterizing waste spills, storm or tsunami damage, and so on). In addition, the team is exploring new organizational partnerships that may lead to the development of a larger, next-generation version of the boat.

Planned upgrades for the current boat, to be implemented as student projects, include the development of additional payload modules, the upgrade of navigation sensors, and the incorporation of higher-level autonomous functions. With respect to navigation, the team is interested in (a) the development of a higher performance coupled navigation and pitch/roll controller, (b) the full incorporation of disturbance feedforward control features to enhance performance in strong currents and winds, and (c) the use of vision-based navigation strategies to avoid obstacles and to automatically dock the boat at the end of an operation. The team is also improving its ability to post-process mapping data to improve map quality; this is largely a function of learning how to effectively use the power of the MB System tool, which has a challenging learning curve. Finally, to achieve unattended operation, the team will incorporate existing, advanced anomaly management systems used by RSL for the operation of NASA satellites to detect, diagnose, and resolve faults and to rapidly notify operators of the state of the boat (Kitts, 2006; Young, Kitts, Neumann, Mas, & Rasay, 2010).

9. SUMMARY

The SCU SWATH boat is a novel USV capable of science-quality bathymetric operations. Its use of a SWATH hull design allows very shallow water operation and provides superior platform pitch/roll stability to enhance the performance of science instruments. Its navigation system allows it to automatically follow a preplanned path with the precision required to efficiently create complete maps of a region of interest. In its current form, the boat meets its design objectives by supporting science-quality missions and by being capable of operating for more than 8 h at a time, with much of that time independent of operator intervention. The student-based development of the system has resulted in a very low-cost system while also playing a major role in a vibrant, hands-on, interdisciplinary educational program specializing in field robotics.

ACKNOWLEDGMENTS

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The authors acknowledge the many students who have contributed to the development and field operation of the system. Student participation in this program has been incorporated into the SCU and MBARI programs in the form of one Master's thesis, independent study projects involving five graduate students, three undergraduate capstone projects involving 11 students, three summer internships, and a marine operations class involving dozens of students.

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