SeaWASP: A Small Waterplane Area Twin Hull Autonomous Platform for Shallow Water Mapping

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ABSTRACT: ***Students with Santa Clara University (SCU) and the Monterey Bay Aquarium Research Institute (MBARI) are developing an innovative platform for shallow water bathymetry. Bathymetry data is used to analyze the geography, ecosystem, and health of marine habitats. However, current methods for shallow water measurements typically involve large, manned vessels. These vessels may pose a danger to themselves and the environment in shallow, semi-navigable waters. Small vessels, however, are prone to disturbance by the waves, tides, and currents of shallow water. The SCU / MBARI autonomous surface vessel (ASV) is designed to operate safely, stably in waters > 1 m and without significant manned support. Final deployment will be at NOAA's Kasitsna Bay Laboratory in Alaska.***

The ASV utilizes several key design components to provide stability, shallow draft, and long-duration unmanned operations. Bathymetry is measured with a multibeam sonar in concert with DVL and GPS sensors. Pitch, roll, and heave are minimized by a Small Waterplane Area Twin Hull (SWATH) design. The SWATH has a submerged hull, small water-plane area, and high mass to damping ratio, making it less prone to disturbance and ideal for accurate data collection. Precision sensing and actuation is controlled by onboard autonomous algorithms. Autonomous navigation increases the quality of the data collection and reduces the necessity for continuous manning.

The vessel has been operated successfully in several open water test environments, including Elkhorn Slough, CA, Steven's Creek, CA, and Lake Tahoe, NV. It is currently is in the final stages of integration and test for its first major science mission at Orcas Island, San Juan Islands, WA, in August, 2008. The Orcas Island deployment will feature design upgrades implemented in Summer, 2008, including additional batteries for all-day power (minimum eight hours), active ballast, real-time data monitoring, updated autonomous control electronics and software, and data editing using in-house bathymetry mapping software, MB-System.

This paper will present the results of the Orcas Island mission and evaluate possible design changes for Alaska. Also, we will include a discussion of our shallow water bathymetry design considerations and a technical overview of the subsystems and previous test results.

The ASV has been developed in partnership with Santa Clara University, the Monterey Bay Aquarium Research Institute, the University of Alaska Fairbanks, and NOAA's West Coat and Polar Regions Undersea Research Center.

Introduction

Students with Santa Clara University (SCU) and the Monterey Bay Aquarium Research Institute (MBARI) are developing an innovative platform for shallow water bathymetry and multi-platform engineering studies. The Small Waterplane Area Twin Hull (SWATH) autonomous surface vehicle (ASV) for multibeam sonar, SeaWASP, features stability in shallow water conditions, reduced draft, minimal manned support, and extendibility for future missions.

Bathymetric data is used to analyze and monitor geography and ecosystems, establish baselines, and perform repeat surveys for a variety of science and societal needs such as health of marine habitats. Shallow water regions like coasts, bays, and estuaries provide numerous and diverse resources to human populations. Mapping of these areas provides the information necessary to use those resources effectively and to manage sustainability. Also, mapping provides a greater understanding of geological and ecological change due to global conditions and human involvement.

Current methods for shallow water mapping often involve small manned vessels with over-board or towed systems. The draft of these vessels pose a danger to themselves and the environment in shallow, semi-navigable waters, limiting the minimum depth of their measurements. Also small vessels are more prone to disturbance by the waves due to the turbid shallow waters and a large waterplane area. The resulting pitch and roll deviations in the multibeam sonar data complicate reconstructing grid and projection visualizations. SeaWASP uses a light weight SWATH boat design to accomplish stability in waves up to 1 m and operations in shallow draft areas less than 0.5 m.

SeaWASP is a student program; students are directly responsible for design, manufacture, integration and test, operations, data analysis, and task management.

SWATH Boat Architecture

The two hulls are fully submerged and connected with vertical struts to an above-water platform, seen in Fig. 1. The boat has a high mass to damping ratio, making it less prone to disturbance and ideal for accurate data collection.

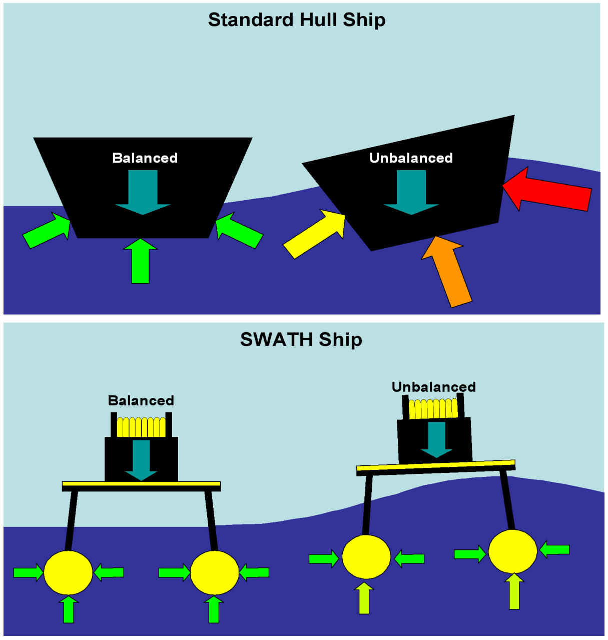

Fig. 1: Mono-hull vs. SWATH [1]

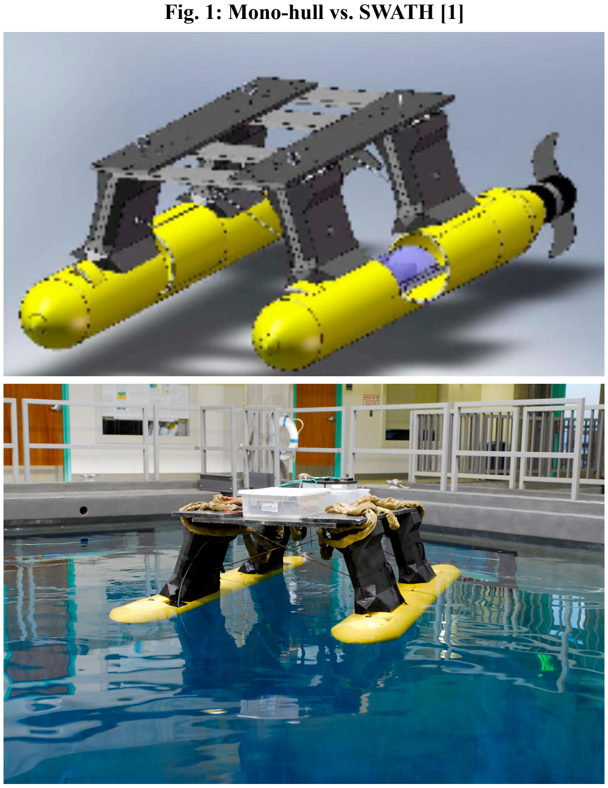

Fig. 2: CAD model of SeaWASP (above); SeaWASP in test tank at MBARI (below)

The primary purpose of the SWATH boat is to support the science mission, shallow water mapping. The boat must be stable in seas up to 1 m, powered for a full day (8 hrs), autonomously controlled, and operable in polar and temperate climates ranging from -10˚ to 60˚ C.

The SWATH boat subsystems are modular and extendable to maximize flexibility. This architecture permits future planning without disrupting mission-critical development. For example, the autonomous control electronics package can be removed, tested, or replaced independently and without affecting the rest of the system, allowing for responsive integration and upgrades. We frequently operate with two different quickly-swappable control packages for varied test scenarios within one deployment. Also, the boat structure is designed positively buoyant with real-time-adaptable, low-volume lead weights for trim - rather than negatively buoyant with limited positive trim - such that components can be added without sinking the boat.

In addition to supporting shallow water bathymetry, the SWATH boat has the potential to be a highly valuable generalized support bus or autonomy test platform. By maximizing the future uses of the boat, we increase its interest to MBARI - as a member of the research fleet - and to SCU - as a flagship of multi-system operations.

Subsystems include structure, power, propulsion and sensing, and autonomous control.

Structure

The SWATH boat structure consists of two fiberglass hollow hulls joined with vertical struts to an aluminum honeycomb platform, as seen in Fig. 2. When deployed, the twin hulls are completely submerged and the platform remains above water.

The hulls contain components that must be submerged (science instruments and motors) and heavy components in order to lower the center of mass (batteries in water-tight containers). The hulls also contain closed-cell foam for overall positive buoyancy and in-water adjustable lead weight pouches for negative trim.

Components that are water-sensitive and ones needing to be accessed from the shore are attached to the platform in water-tight boxes: power distribution and autonomous control electronics, communications, and on-board data storage.

Power

The boat is equipped with a 12 V and 24 V power bus supplied by six 12 V 84 A-hr Sun Xtender PVX-840T sealed lead-acid batteries. At full duty cycle and 60% depth of discharge, the motors will last 8.4 hours and the instruments and electronics will last 10.2 hours; this satisfies the mission requirement of 8.0 hours.

Each battery is housed in a 3/8” ABS plastic water-tight box with 3/8” polycarbonate lid, 1/8” latex rubber

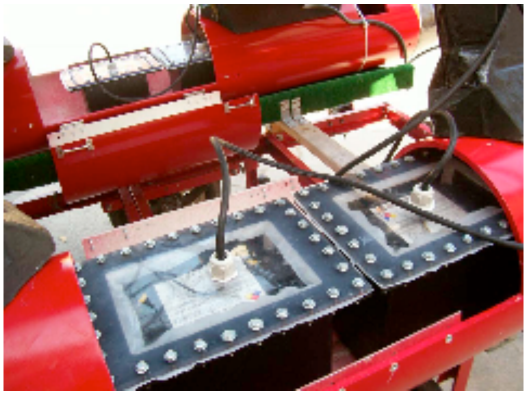

Fig. 3: Batteries installed in hulls watertight boxes

gasket, and 1/4” bolt closure, as seen installed in the twin hulls in Fig. 3. All boxes are verified non-leaking at 1 m up to 72 hours in accordance with IP-68.

Sensing and Propulsion

The boat is propelled by two Minn Kota RT55 brushed DC electric trolling motors, modified to be mounted at the back of each hull. The motors are activated by a RoboteQ AX3500 controller board, which accepts inputs from the autonomous controller.

Sensors include a Garmin 18 GPS unit and compass. We also have a Teledyne RDI© 600 kHz Workhorse™ Doppler Velocimeter Log (DVL). For pitch and roll we are currently using a Sonardyne© Radian™ attitude heading and reference unit (AHRS), pictured in Fig. 4.

Fig. 4: Sonardyne Radian AHRS Unit

Taken together with the right filtering we are able to recreate multibeam maps with decent accuracy and place them in a global framework. Heave sensing is still not well handled to complete a sensor suite for full functionality and testing. However we have recently acquired, in the same manner as all the instrumentation – donations – a Crossbow AHRS that may offer us better heave sensing. This unit is yet to be integrated but will be as part of the next phase. The Radian and the Crossbow will be compared and filtered to calibrate performance and suitability for the purpose of mapping. Currently the SCU team doesn’t have the funds for a better unit but we are searching for a vertical reference unit (VRU) specifically built for this purpose to eventually become the core sensor.

Investigations into possibly better instruments such as a fiber optic gyro (FOG) or ring laser gyro (RLG) are also going on simultaneously with modeling and associated efforts to follow. The belief being SCU will either get funding to afford a unit, costs will drop potentially to be more affordable, or like other instrumentation we can inherit an older unit from a research institute. This model has proven to be true to date, but until an inertial navigation system can be installed the SeaWASP will suffer some errors in map placement and quality.

Autonomous Control

Autonomous control is necessary to reduce manned support obligations, collect data over large regions, and, most importantly, take measurements in a precise and easily post-processed pattern. Control electronics and software were developed by Santa Clara University students.

SeaWASP uses a trajectory controller, which defines a pattern of straight lines between a list of desired waypoints. Straight, parallel lines in a mow-the-lawn pattern with two or three cross-tracking lines most simplify post-processing. The boat is allowed a certain amount of time to travel between two waypoints. The boat’s X-Y location (with inputs from the GPS and compass) is measured against a linear interpolation between the waypoints. The controller then minimizes the cross-track and in-track errors, shown graphically in Fig. 5. The cross-track error is the perpendicular distance from the boat to the desired track, or the distance off track. The in-track error is the distance from this cross-track intersection point to the desired point along the trajectory, or the distance ahead or behind.

SeaWASP uses proportional linear controllers to correct heading and velocity and minimize tracking errors; the algorithm scheme is shown in Fig. 6. For in-track error, the error is multiplied by a gain and added to the velocity, such that the boat speeds up when behind and slows down when ahead. Cross-track errors are handled similarly. The error is multipled by a gain and added to

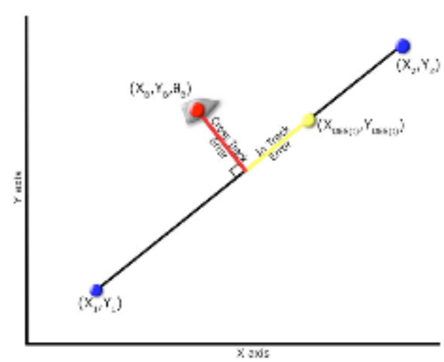

Fig. 5: Trajectory Control Concept Diagram, in which the boat travels a straight line between two points.

the heading, so the boat assumes an intersecting path to the trajectory rather than a parallel or divergent path.

The trajectory controller is simulated in Simulink; the results of one simulation are shown in Fig. 7.

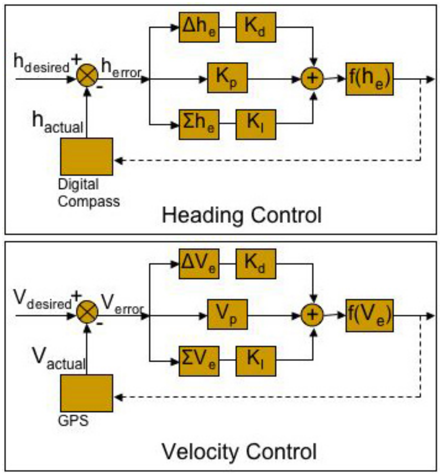

Fig. 6: Implemented control system

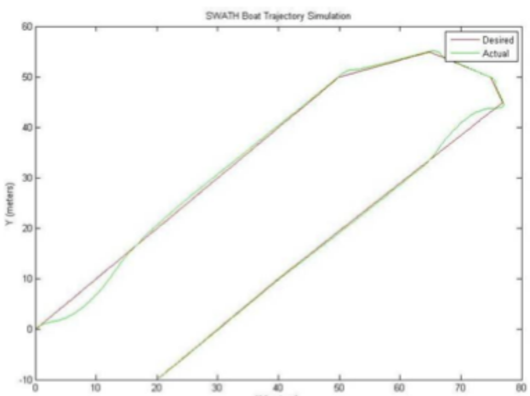

Fig. 7: Simulink simulation of the trajectory controller. The red line is the desired trajectory along five waypoints, the green line is actual path taken.

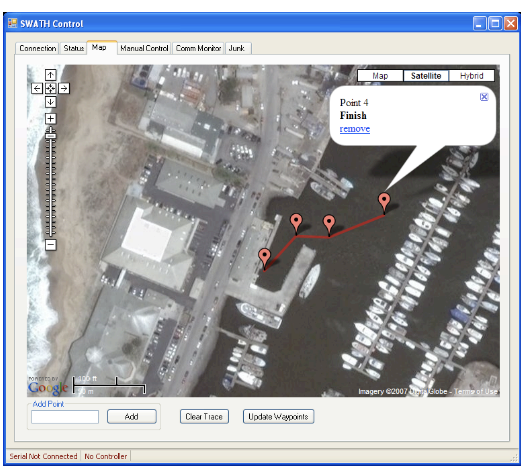

Fig. 8: Waypoint and track line in Google Earth

Science Architecture

Autonomous navigation increases the quality of the data collection and reduces the necessity for continuous manning. Looking at the track lines in Fig. 9 it can be seen that even experienced pilots cannot maintain ideal lines maximizing data quality, resulting in extra work for the data team on shore.

The science instruments must produce shallow water bathymetric maps with < 0.5 m vertical resolution. Autonomy, and the resultant straight-line path shown in Fig. 10, increases resolution and accuracy in all 3 physical dimensions. Accuracy is directly related to the control system and behavior of the vehicle in autonomous modes of operation.

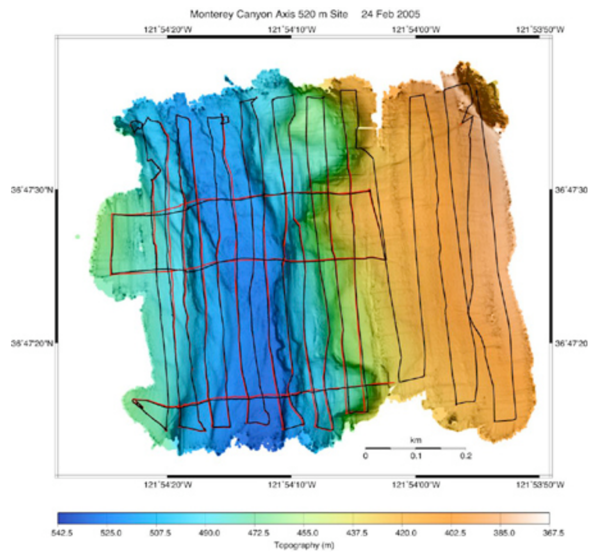

Fig 9: Multibeam mapping accomplished by human pilot using the ROV Ventana.

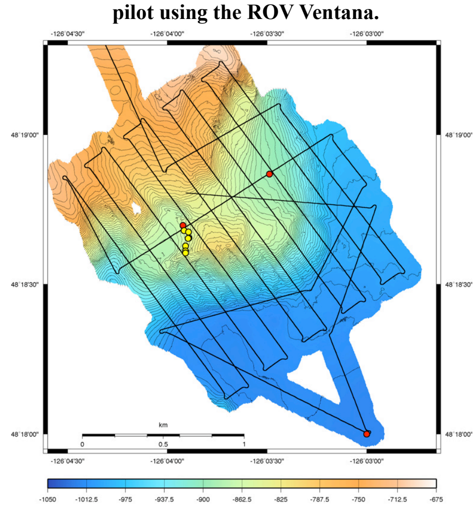

Fig. 10: Typical flight lines of an autonomously controlled vehicle performing multibeam mapping.

To accomplish this, data is collected with a multibeam sonar and several support instruments and post-processed using in-house MBARI mapping software, MB-System. Data is stored onboard to minimize dependence on a strong radio downlink. It may be viewed in real time at the support station via a local area wireless network. All components are powered on the SWATH boat bus.

Instruments

The primary science instrument is an Imagenex Model 837 DeltaT-Head Multibeam Sonar, pictured in Fig. 11 [2]. The DeltaT-Head is readily available to most oceanographic laboratories at relatively low cost. In shallow water applications, the resolution is acceptable for high quality mapping.

The multibeam is used in concert with a Teledyne Workhorse Navigator Doppler Velocity Logger (DVL), Crossbow CXL02LF3 Attitude and Heading Reference System (AHRS), and Garmin 18 GPS unit. These instruments provide calibration support for the sonar data: pitch and roll, heave, and position plotting, respectively.

MB-System

In order to be maximally compatible with other MBARI projects, SeaWASP utilizes the MBARI-developed multibeam mapping software suite, MB-System, shown in Fig. 12. MB-System is an open source package that enables interactive mission planning, data editing, and two- and three-dimensional visualization of numerous multibeam data formats. The newest beta release, version 5.1.1beta21 on July 20, 2008, incorporates reading and writing of DeltaT-Head data. Because DeltaT-Head data formerly ran natively on only one software program (CARIS), this open source addition to MB-System is a significant increase in usability of the Imagenex instrument for other cost-constrained programs.

Support Components

Data is transferred via serial or ethernet protocol to an onboard Dell Latitude ATG D630 laptop. The onboard laptop is connected through Remote Desktop to an identical laptop at the support station via a D-Link 2.4 GHz WBR-2310 Ricochet modem on the SWATH boat.

Results

SeaWASP's success is measured in three deployment phases: Local Proof of Concept, Off-Site Proof of Concept, and Science Operations. In each phase SeaWASP must demonstrate both engineering support and science capabilities. To date, we have achieved significant success in both Proof of Concept phases and are preparing for the final Science Operations deployments.

Fig 11: Imagenex Delta T Head Profiling Multibeam

FREQUENCY	**260 kHz**
TRANSDUCER BEAM WIDTH	**(nominal) Receive: 120º x 3º Transmit: 120º x 3º**
EFFECTIVE BEAM WIDTH	**3º, 1.5º, 0.75º**
BEAM RESOLUTION	**120, 240, 480**
RANGE RESOLUTION	**0.2 % of range**
MIN. DETECTABLE RANGE	**0.5 m**
MAX. OPERATING DEPTH	**300 m**
FRAME RATE	**Up to 20 fps**
WEIGHT: In Air	**2.49 kg (5.5 lbs)**
WEIGHT: In Water	**0.7 kg (1.5 lbs)**

Table 1: Delta T Head Hardware Specifications

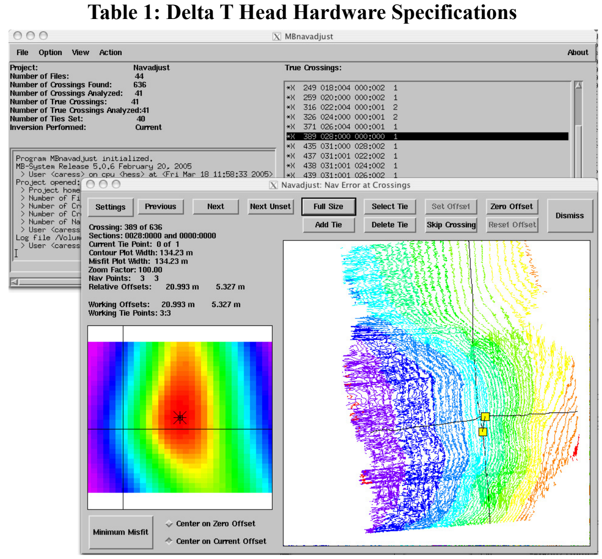

Fig. 12: Typical screen for error correlation correction of navigation in MB-System.

In Local Proof of Concept, SeaWASP is deployed in a controlled environment close to shore, like a harbor, and close to both basic ground support and extended lab support. The boat is run as it would be in a full deployment, but in an extremely sheltered environment near all possible troubleshooting assets. SeaWASP demonstrated full system operations in Moss Landing Harbor between Summer 2007 and Summer 2008. Data

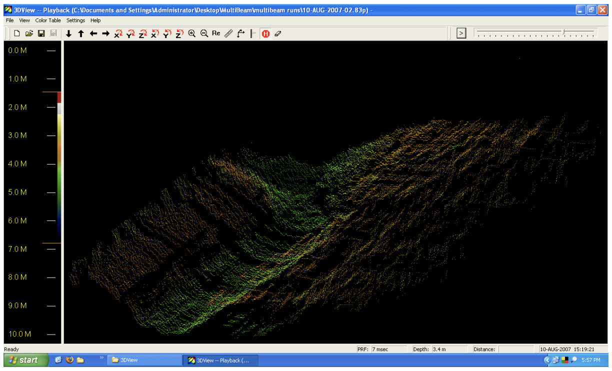

Fig. 13: Data from Moss Landing Harbor, sketched full-size in cascading 2D on Imagenex-supplied software.

from a non-autonomous cruise in the Harbor is shown in Fig. 13.

Off-Site Proof of Concept removes the boat from the laboratory and explores more advanced environments, like a slough or lake, as pictured in Fig. 14. The crew gains experience assembling the entire mission and troubleshooting with limited assets. New challenges are expected to arise in new physical environments. SeaWASP deployed in Elkhorn Slough and Stevens Creek in California and Lake Tahoe in Nevada in Summer and Fall of 2007. Each deployment included at least one subsystem failure, but due to the ingenuity of the engineering team, science data was collected successfully. For example, at Stevens Creek a leaking battery discovered mid-deployment shortened the cruise but did not inhibit data collection up to that point. At Lake Tahoe, a power surge likely due to back emf from the motors disabled the propulsion subsystem. However, the boat was towed by a kayak and data collected. Though SeaWASP has not yet demonstrated reliable full system operations in off-site conditions, every subsystem has been independently verified and the engineering crew has proved resilient to difficulties. As seen in Fig. 15 and Fig. 16, though data collected was limited, it clearly demonstrates SeaWASP's ability to create bathymetric maps. Local deployments in Summer 2008 were focused on upgrades to eliminate issues from the off-site cruises.

Science Operations will commence between Spring and Summer 2009 in the San Juan Islands, Washington, and NOAA's Kasitsna Bay, Alaksa. The boat will be deployed off-site with the goal of collecting quality science data for a specific customer. The collection site for Kasitsna Bay is circled in Fig. 17.

The Summer 2008 upgrades are nearly complete. Completed upgrades include the addition of two batteries for extended power; higher quality battery box components to achieve IP-68; power redistribution; long-duration, high-durability, outdoor laptops; AHRS integration; Imagenex DeltaT-Head data reading and writing

Fig. 14: Off-site deployments in Steven's Creek (above) and Lake Tahoe (below).

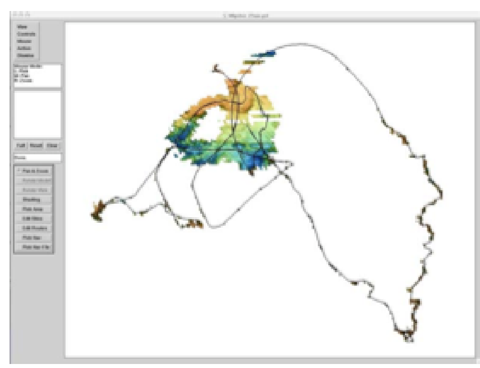

Fig. 15: Bathymetric data collected at Steven's Creek and visualized in false-color relief in MB-System; the dark line is the cruise path.

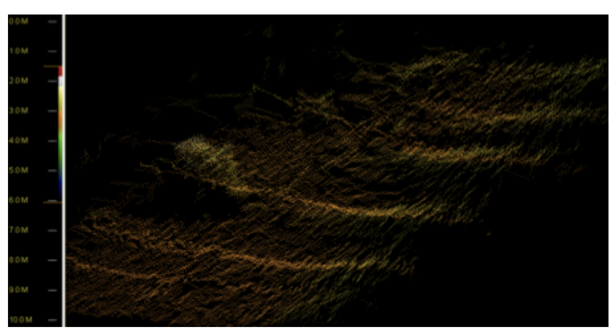

Fig. 16: Lake Tahoe data, visualized in cascading 2D in Imagenex-supplied software.

Fig. 17: Kasitsna Bay (highlighted circle) across from Homer, Alaska.

package for MB-System; wireless network installation for real-time data monitoring; and a new trajectory control electronics and software package. Pending upgrades include additional structural positive buoyancy; new AHRS installation; instrument calibration; and installation of marine-grade wire harness interconnects. Upgrades will be followed by three off-site tests, again in Elkhorn Slough, Stevens Creek, and Lake Tahoe between Fall 2008 and Spring 2009. Science Operations follow immediately, at the latest in Summer 2009.

Future Work

Having successfully deployed in several test scenarios, SeaWASP is being prepared for contracted science mission deployments in the San Juan Islands, Washington, and NOAA's Kasitsna Bay, Alaska, through 2009 (Fig XX).

Because the SWATH boat bus was designed with a flexible and upgradable architecture, SeaWASP will then be extended for future science and engineering use at MBARI and SCU. At MBARI, SeaWASP fills a shallow water niche by covering areas not accessible by the institute's AUV's or ROV's. The SWATH boat will be outfitted with new science payloads as needed by MBARI researchers.

SeaWASP incorporates control electronics and software developed by SCU students that are compatible with several other SCU systems, including UAV's, ROV's, and small satellites. In future work, the students will integrate several of these systems for cooperative autonomous controls, beginning with an ensemble of duplicate SWATH boats. The ensemble will be used as a test platform for multi-system autonomous operations.

Acknowledgments

SeaWASP is developed in partnership with Santa Clara University, the Monterey Bay Aquarium Research Institute, the University of Alaska Fairbanks, and NOAA's West Coast and Polar Regions Undersea Research Center.

Students are directly responsible for nearly all aspects of the project, including design, manufacture, integration and test, operations, data analysis, and task management. Since 2004, the program has contributed to numerous Masters theses, senior design projects, undergraduate/graduate research opportunities, and internships at SCU and MBARI.

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