PAPER

BathyBoat: An Autonomous Surface Vessel for Stand-alone Survey and Underwater Vehicle Network Supervision

AUTHORS
Hunter C. Brown
University of Michigan

Liza K. Jenkins
Michigan Tech Research Institute

Guy A. Meadows
University of Michigan

Robert A. Shuchman
Michigan Tech Research Institute

ABSTRACT

Exploration of remote environments, once the domain of intrepid adventurers, can now be conducted in relative safety using unmanned vehicles. This article describes the joint University of Michigan (UMich) and Michigan Tech Research Institute's project to design and to build a new autonomous surface vessel (ASV) for use in research, education, and resource management as well as in the commercial sector.

Originally designed to assist with bathymetric surveys in the wilderness of northern Alaska, the *BathyBoat* has become a test-bed platform for new research in collaborative heterogeneous underwater robotic search and survey missions in ports, harbors, lakes, and rivers. The UMich Marine Hydrodynamics Laboratories are actively researching autonomous technologies such as cooperative navigation, surface vessel control, and multivehicle search and survey using the *BathyBoat* and the UMich Perceptual Robotics Laboratory's *Iver2* autonomous underwater vehicles.

This article presents an overview of these research topics and highlights relevant real-world testing and recent missions involving the *BathyBoat* ASV on Alaska's North Slope, the harbors of Illinois, and various riverine environments in Michigan.

Keywords: ASV, Remote survey, Cooperative, Autonomous test bed, Network

Introduction

Within the last decade, researchers have become increasingly reliant on teams of cooperative autonomous vehicles to survey and to search environments more efficiently than using a single vehicle (Cronin et al., 2008, Madhavan et al., 2002, Barnes et al., 2007). Swarm robotics have gained a large following in the land-based variant, and heterogeneous vehicle networks have also experienced a surge in interest. Current vehicle networks combine the use of air, sea (and subsea), and land-based vehicles to achieve various mission goals in ever decreasing time. Some of these networks even organize themselves automatically (Werfel et al., 2007).

In an effort to increase the productivity of such robotic vehicle teams, the Marine Hydrodynamics Laboratories (MHL) is actively researching several new algorithms for autonomous vehicles involving cooperative navigation, surface vessel control, and multivehicle search and survey. To test these algorithms in real-world environments, the University of Michigan (UMich) and the Michigan Tech Research Institute (MTRI) have partnered to develop a new autonomous surface vessel (ASV) that can perform stand-alone scientific and security surveys or supervise teams of underwater vehicles working together to quickly survey an area. This article describes these research efforts and offers a detailed description of the test-bed vehicle (Figure 1).

Ongoing research at many universities around the world is focused on reliability, control, communication, and group control and organization of autonomous vehicle networks. The University of Pennsylvania's General Robotics, Automation, Sensing and Perception (GRASP) Laboratory (Pimenta et al., 2008) and the University of Tennessee's Distributed Intelligence Laboratory (Parker and Tang, 2006) are investigating reliability issues of self-organizing teams of heterogeneous

FIGURE 1

The MHL/MTRI *BathyBoat* at the UMich Lurie Reflecting Pool.

vehicles in hostile environments. By leveraging architectural, behavioral, and functional models of groups known to biologists, these researchers hope to develop new algorithms for multivehicle coordination and control.

Princeton University (Fiorelli et al., 2006) is experimenting with Webb Research Corporation Slocum Gliders to investigate control of underwater glider fleets. In the field trials, each vehicle relied on inertial navigation (dead-reckoning) techniques, surfacing every two hours to obtain a GPS fix and correct any accumulated drift errors in the position estimate.

Similarly, the Virginia Tech Autonomous Systems and Controls Laboratory (ASCL) is studying coordinated control of multiple vehicles over extremely low bandwidth communication networks such as acoustic modems (Gadre et al., 2008). The goal of this research is to devise new strategies for message passing and directive issuance in underwater environments where current technological limitations prevent high-speed communication. The ASCL currently uses small autonomous underwater vehicles (AUVs) with a diameter less than approximately 12 cm (5 in) with onboard GPS at the surface and dead-reckoning underwater for navigation in their research.

The University of Portugal has constructed and tested several heterogeneous cooperative systems in real-world scenarios comprised of AUVs, ROVs, ASVs, and unmanned aerial vehicles. In 2006, the group conducted swarm field trials in Monterey Bay using a Hydroid Remus vehicle and the Naval Postgraduate School's ARIES vehicles (Marques et al., 2007, Martins et al., 2009). Communication between two underwater vehicles was conducted through acoustic links; however, no surface or aerial vehicles were used in the trial.

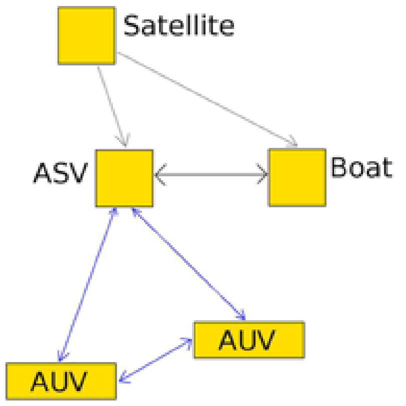
Engineers at the University of California San Diego (UCSD) are using a different approach to solve the same class of problems. The UCSD team was recently awarded a National Science Foundation grant to explore an underwater Lagrangian (drifting) buoy network that communicates via acoustic modems. This system has the capability to perform higher spatial and longer temporal scale sampling than conventional methods, but at the cost of deploying tens to hundreds of devices at numerous locations.

Deployments involving large vehicles like the University of Portugal or many small vehicles, such as UCSD, have remarkable logistic and financial requirements; the cost of these missions can run into the hundreds of thousands of dollars per mission. The staggering cost of shipboard time—from $20,000 to $40,000 per day— is enough to halt many projects even before the actual deployment. Also, environmental factors such as limited access to automobiles, federally protected land, or hostile environments (e.g. extreme temperatures or unstable terrain) often prevent the use of large vehicles.

Each of the above projects is challenged by issues of transportation, logistics, cost, and communication between vehicles. To meet these design constraints, the UMich MHL and the MTRI designed and constructed a small, low-cost ASV (Figure 1) for remote bathymetric surveys and distributed ocean sensing. In addition to hosting a full suite of environmental sensors, the new ASV, christened *BathyBoat*, also serves as a command and control station for underwater vehicles through the use of its onboard electronics and acoustic communications package. The *BathyBoat* can communicate with the PeRL *Iver2* (Figure 2) vehicles by transmitting either mission commands or status requests through an optional acoustic modem. Each underwater vehicle can be polled within the status request framework and the results used to optimize simultaneous localization and mapping (SLAM) solutions or to assist in mission decision making.

FIGURE 2

Multivehicle cooperative search organization.



Research

The MHL robotics group is conducting three main areas of research involving the *BathyBoat* ASV: (1) autonomous navigation, (2) control for ASVs, and (3) cooperative searching algorithms. This section provides an overview of each area as well as a discussion of direct real-world applications.

Autonomous Navigation

One of the major research endeavors at the MHL is autonomous navigation. The partnership between MHL and PeRL allows new navigation algorithms to be developed using a suite of test-bed platforms from underwater vehicles to surface vehicles and even unmanned aerial vehicles (Meadows et al., 2009). Two of the major components of autonomous navigation are cooperative navigation between multiple vehicles and navigation when sensor data are restricted or inaccessible.

Cooperative Navigation

Many research institutions have recently begun to explore the benefits of using multiple vehicles to perform various marine missions. In addition to faster coverage of an area, the use of multiple subsea vehicles also results in more accurate positioning information (Bahr et al., 2009, Brown et al., 2009).

The introduction of a surface vehicle to the network of underwater vehicles offers a tremendous benefit by providing precise navigation information retrieved from GPS signals. Once an accurate position for the surface vessel is known, through GPS, the direct measurement of the relative positions of the underwater vehicles can be determined by intervehicle one-way travel time time-of-flight ranging. Each vehicle broadcasts a signal with an embedded timestamp, and the slant-range positions for every vehicle can be estimated to within a high degree of accuracy.

Reduced Instrument Navigation

In the field of robotics, there is a well-known thought experiment known as the kidnapped-robot problem (Engelson and McDermott, 1992). Imagine a robot that is suddenly placed in a completely unknown environment and must accomplish some goal. The robot must create a map and localize itself within that map for navigation purposes. The solution to this problem is one goal of the PeRL research software onboard the *Iver2* vehicles. A related problem is known as the *Urban Canyon* problem. Ground-based robots often rely on GPS information for navigation purposes. In urban settings, however, the tall city buildings block or distort the GPS to an unusable state (Vicek et al., 1993). Without GPS information, most ground vehicles revert to dead-reckoning or state-estimation techniques for localization (Cui and Ge, 2003).

In the marine environment, the same phenomena occurs when an ASV passes underneath large bridges, docks, and piers; in these cases, we must rely on inertial sensors and state estimators to guess our location. Most surface-based robotics research assumes access to GPS positioning information and focuses on control or communications schemes. The MHL is actively developing new algorithms that blend visual information with more traditional inertial guidance systems to solve localization and mapping problems when outside the normal range of GPS signals.

On August 1, 2007, the I-35 W bridge across the Mississippi River in Minneapolis, Minnesota, collapsed during rush hour, killing 13 and injuring over 100 motorists. This tragic incident, and several others like it, have prompted a reexamination of the nation's approach to maintaining and inspecting critical infrastructure. One direct application of the MHL research is the autonomous inspection of bridge and pier pilings. Many bridges and piers are large enough to block GPS signals from reaching small surface craft directly below the superstructure. Visual information such as the relative locations of pilings or other fixed landmarks, in combination with accelerometers and gyroscopes, can be used to produce a highly accurate estimation of the vehicle position. Underwater vehicles use tactics quite similar to this, although visual information is often of limited use in underwater environments (Brown et al., 2009).

Control for Autonomous Surface Vessels

Another major research effort by the MHL is that of ASV control. ASVs have been experimented with since the early 1990s (Chaumet-Lagrange et al., 1994). Control systems for these vessels have undergone a remarkable transformation in both precision and complexity. Today, nautical control systems not only use GPS waypoints to meet mission objectives but factor in waves, currents, weather, and other phenomena to determine optimal paths (Fossen, 2002). Our research centers on the optimal waypoint and trajectory following of small direct-drive and differential-drive autonomous vehicles and real-time track modification to reduce wave influences.

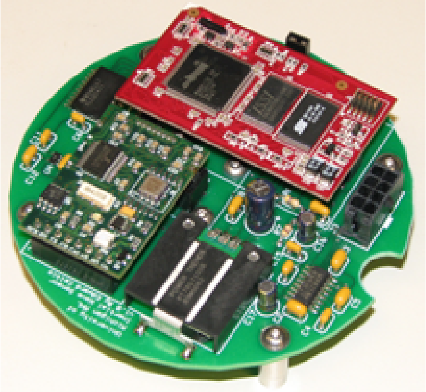
Wave Measurement

It comes as no surprise that information about the sea state is critical to autonomous surface craft (Bingham et al., 2009). Wave energy has been a focus of research for hundreds of years, but only with the recent advances in microprocessors have scientists been able to conduct accurate long-term experiments. The MHL leverages technology born on offshore buoy platforms to minimize the effects of waves on missions involving small ASVs.

The National Data Buoy Center, an organization created solely to design, build, maintain, and research buoy technology, has developed a strong program in wave monitoring on the basis of many well-known wave papers (Sverdrup and Munk, 1947; Longuet-Higgins et al., 1963; Steele and Earle, 1991). The algorithms described in these papers have been modified by the MHL and implemented in the form of the low-cost MHL inertial wave sensor (IWS) for use on university buoys (Figure 3).

FIGURE 3

The MHL IWS.



The IWS consists of a three-axis accelerometer (ADXL330), a digital compass (HMR3300), and an embedded controller (Rabbit RCM3600) to perform onboard calculations. Data from the sensors are sampled at 4 Hz and analyzed in the frequency domain by performing a discrete Fourier transform. The National Data Buoy Center first-five Fourier coefficients are calculated using the co- and quadrature spectra of the wave train and stored for use in forecasting models. A modified IWS is slated for inclusion on the MHL *BathyBoat* to allow the vehicle to monitor and react to sea-surface changes in the form of waves.

In Earle et al. (2002), a system is described that is mounted on an AUV and determines wave parameters by measuring vehicle motion and pressure fluctuations. In our case, we are limited to the measurement of only vehicle motions. One advantage, however, is that ship motions in waves are well known and have been well characterized through decades of research. By recording the roll, pitch, and heave motions, in addition to accelerations along the major axes of the ASV, we can estimate the directional and nondirectional wave spectra. This research has applications in the direct replacement of traditional coxswains with automated systems that are both smaller and lighter.

Perception-Driven Control

In conjunction with PeRL, the MHL is also investigating the use of real-time algorithms that react to the environment to make mission decisions (Brown et al., 2009). Although the PeRL work is focused on integrating feature-rich zones into a SLAM framework, we are concerned with providing detailed surveys of a previously bounded region (including areas void of salient features). Algorithms under development by the MHL use side-scan sonar data to gather data on salient bottom features then locate and describe the spatial distribution of a region of interest using machine vision techniques. Once a description of the site is complete, an optimal search pattern can be derived to produce the most efficient search of the region of interest.

Cooperative Search

In combination with navigation and control research, the MHL is working to optimize cooperative search and survey schemes. Multivehicle operations promise efficient exploration by pooling resources and environmental data during missions. Most prior research in the ASV community, in support of underwater vehicle networks, is focused on using the ASV simply as a communications gateway to shore stations. Our research, however, is focused on using the ASV not only as a communications gateway but also as a navigational aid and a command and control center for the entire system. Here, our current scheme uses an ASV to conduct long-range communications and make mission level decisions, a mid-water vehicle to conduct large-area surveys, and a vision-equipped underwater vehicle to perform high-resolution scans of targets identified by the mid-water vehicle.

System Overview

The platforms used by the MHL to assist with the real-world validation of research algorithms are the new ASV *BathyBoat* and the OceanServer *Iver2* AUV. The *BathyBoat*, at the surface, is in constant communication with the two underwater vehicles and also other surface or shore-based platforms (Figure 2). To ensure standardized communication between each heterogeneous agent in the system, a common framework has been implemented on each vehicle. The onboard software architecture is composed of the multiprocess, open-source Lightweight Communications and Marshalling (LCM, 2010) interprocess communications library. The library was developed by the MIT Defense Advanced Research Projects Agency Urban Grand Challenge team (Leonard et al., 2008, LCM, 2010). An overview of the *BathyBoat* is covered in this section. Details about the *Iver2* vehicle can be found in Brown et al. (2008).

BathyBoat

Bathymetric survey costs for a single 139-ha (344-acre) lake within the continental United States typically range from $10,000 to $25,000 using industry standard techniques (Bergman et al., 2006) and cost considerably more on the North Slope of Alaska because of the additional logistics involved. In an effort to reduce these costs, UMich and MTRI collaborated to design and build a low-cost ASV sensor platform at a fraction of the price ($2,000, a full order of magnitude); this platform can survey, log, and transmit real-time data in a fully autonomous mode of operation. In addition, the *BathyBoat* also serves as a development platform for MHL and MTRI algorithm research such as remote-sensing algorithms and autonomous navigation schemes.

To support the real-time data collection and transmission objectives, a suite of hydrographic sensors were integrated into a UM-designed hull. To facilitate the low-cost aspect of the vehicle, trade-offs were made with regard to final sensor selection. A Honeywell HMR3300 electronic compass (including roll and pitch sensors) provides required information to the processing hub for autonomous navigation. A Garmin 16 HVS GPS compliments the HMR3300 by providing worldwide location and timing information. A RadarSonics 250 acoustic depth sensor was chosen because of its size and ease of integration into the *BathyBoat* hull. Conductivity is measured using a Vernier CON-BTA conductivity sensor, whereas temperature is measured with a National Instruments LM35. Both the CON-BTA and the LM35 are compact, low-cost instruments and provide measurements within acceptable specifications for the mission the *BathyBoat* typically conducts. Lastly, a Humminbird wireless fish finder was affixed to the transom of the vessel. The fish finder, however, has been of limited use because of the range limitations of its integrated transmitter.

Also installed was a Digi International XTend Radio modem. A custom deck and a passive directional indicator were added using special composite/aluminum fabrication techniques and contrasting paint colors. The physical envelope of the vehicle was constrained to allow transportation in a Bell JetRanger III helicopter (Figures 4 and 5), thereby enabling access to remote lakes in the Arctic Circle.

FIGURE 4

Moving the *BathyBoat* from a helicopter for deployment on the North Slope of Alaska.

FIGURE 5

Control of the *BathyBoat* from inside a helicopter in the Arctic National Wildlife Refuge.

The hull of the *BathyBoat* is 0.97 m (38 inches) in length, with a draft of 0.10 m (4 inches). The minimal draft, in combination with a recessed propeller, allows the vehicle to operate in extremely shallow areas in which biological fouling is a concern. The interior cavity is lined with expandable foam to provide emergency buoyancy in the case of flooding. The vehicle weighs 32 lb with batteries and can easily be unloaded, ported, and launched by a single person.

The *BathyBoat* can be outfitted with a wide range of environmental sensors for different applications. The heart of the *BathyBoat* is a Digi International Rabbit LP3500 low-power (less than 20 mA fully operational) single board computer (Digi International, 2010). Software written by the MHL and loaded into the single board computer memory controls logging, radio communication, serial communication, autonomous navigation, and autonomous speed settings. A special printed circuit board inside the vehicle accepts sensors reporting data via RS-232, RS-485, voltage output, current output, or frequency output and connects each with the LP3500. The same printed circuit board also provides regulated +5 VDC and +12 VDC power for sensors from a +12 VDC sealed lead-acid battery source. The open hardware and software architectures allow new sensors to be integrated with minimal effort. See Table 1 for standard sensors integrated in the current platform. A future environmental package including chlorophyll, dissolved oxygen, turbidity, and other sensors is currently under review for inclusion on the *BathyBoat*.

The *BathyBoat* is operated in one of two control modes: autonomous or manual. In autonomous mode, the vehicle follows a predefined bearing or performs GPS waypoint navigation. GPS waypoints, bearing, and sensor options can be modified in real time through a long-distance radio modem with a range of up to seven statute miles. Anytime the vehicle is within R/C radio range, a field operator can

TABLE 1

Integrated sensors on the *BathyBoat*.

Sensor	Variable	Update Rate	Accuracy	Range
Honeywell HMR3300	Heading, roll, pitch	8 Hz	1° (heading), 0.5–1.2° (roll, pitch)	360°, ±60°
Garmin GPS-16LVS	Time, position, track	1 Hz	3–10 m	–
RadarSonics Model 250 Sonar	Water depth	1 Hz	0.1 m	0.4–135 m
National Instruments LM35		1 Hz	±3/4°	−55 to +150°C
Vernier Con-BTA Probe		0.2 Hz	±1%	0–2000 μS/cm
Humminbird RF15 Wireless Fish Finder	Depth, fish	125 kHz	–	30 m

assume manual control by powering a handheld radio control transmitter. In manual mode, access to the full suite of sensors is still available in real time through the radio modem (Figure 4). Both manual control and radio modem control were demonstrated from an airborne helicopter during the most recent missions in Alaska.

During testing, the *BathyBoat* was powered by two +12 v lead-acid batteries, each with a capacity of 7 amp hr. The vehicle maintained an average speed of 0.7 m/s (2.3 feet/s) for 2 h, traveling 5.5 km (3.4 miles). At a speed of 0.52 m/s (1.7 feet/s), the vehicle ran for over 3 h and traveled approximately 5.6 km (3.5 miles) (Figure 5).

Field Trials

The *BathyBoat* and *Iver2* vehicles have held trials in the states of Michigan, Illinois, and Alaska. An overview of these missions and trials is presented here. Figure 6 shows the locations of various test sites around the country. In northern Michigan, the *BathyBoat* was tested at the UMich's Biological Station on Douglas Lake and Harrisville Harbor on the eastern coast of Michigan. In southeastern Michigan, the vehicle was tested in Ann Arbor at several locations. The southwestern Michigan tests and missions were conducted on the Grand and Kalamazoo Rivers. A harbor study was conducted in Waukegan, Illinois. Most recently, the *BathyBoat* surveyed several lakes on the North Slope of Alaska, near Helmerick's.

Michigan

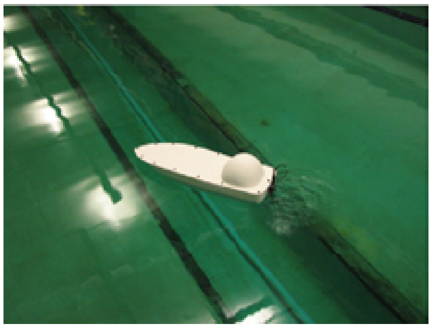
Initial testing of the *BathyBoat* ASV was conducted at the MHL physical modeling basin (Figure 7) and Wild Pond in Ann Arbor, Michigan, in 2007 and 2008. Basic hull integrity, propeller sealing, and manual control were thoroughly tested and verified in the physical modeling basin. The model basin measures 110 m (360 feet) in length, 6.7 m (22 feet) wide at the water surface, and has an average depth of 3.2 m (10.5 feet). After successful trials in the basin, testing was continued at Wild Pond. Autonomous navigation, radio communication, and remote tasking were verified through a varied regimen of trials. Rudder ranges were characterized, and algorithm parameters were identified experimentally to achieve the best performance at a spectrum of speeds. A depth map of the pond was produced under manual

FIGURE 6

Field trial locations in Alaska, Illinois, and Michigan.

FIGURE 7

BathyBoat trials at the MHL physical modeling basin.

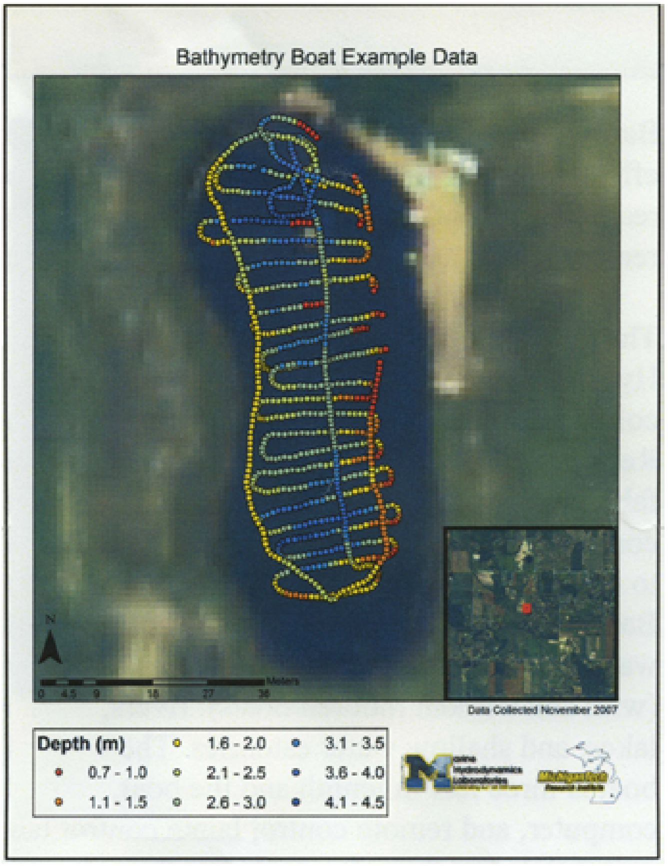


control, and autonomous heading following was also demonstrated (Figure 8). A contour map was then constructed using the bathymetry data collected during the trials (Figure 9).

The *BathyBoat* was also used to perform a harbor dredging study in Harrisville, Michigan. Here, the boat sampled over 3,000 data points inside the harbor to inspect the results of recent dredging activities. The vessel was maneuvered along a 100 m line-of-sight path five times while scanning at a rate of 1 Hz to characterize the accuracy of the depth sensor. Maximum depths ranged from 1 to 2 m in the five-pass lane and 0.5 m to over 4 m for the entire survey. A maximum variation of 10 cm was observed over the five trials at corresponding data points. This is attributed to the depth sounder model and can be improved by replacing the depth sounder with a higher-resolution sensor.

FIGURE 8

Bathymetry data taken during the 2008 Wild Pond survey.



In 2009, riverine studies were performed for a Grand Rapids civil engineering firm in Allegan and Plainfield Township, Michigan. The *BathyBoat* was used to collect bathymetric data on a section of the Grand River to determine the feasibility of spanning the river bottom with a water pipeline and also used to survey the Kalamazoo River in the town of Allegan for expansion of their drinking water treatment delivery system. Both of these sites are located near the western coast of Michigan.

Illinois

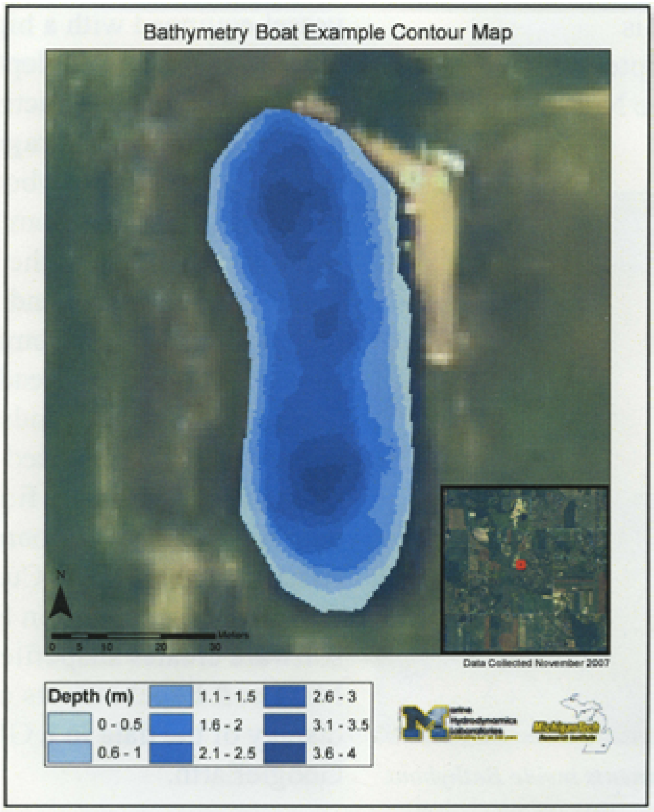
In September of 2009, the *BathyBoat* was deployed to Waukegan, Illinois, for extensive harbor surveys. A local firm was interested in possible sediment agitation from surface propellers. The *BathyBoat* proved conclusively, after performing hundreds of transects, that the effects of surface propellers on the harbor seabed were negligible. This mission demonstrated the capacity and viability for harbor monitoring and security patrols to be performed autonomously.

Alaska

The North Slope Science Initiative (NSSI) was established in 2003 as the intergovernmental endeavor to address the critical information requirements essential for sound resource management and decision making on the North Slope of Alaska. NSSI created the North Slope Water Characterization Project to support the development of innovative and cost-effective methods to collect essential data required to support their mission. As part of the project, NSSI partnered with MTRI and UMich to use the *BathyBoat* and other sensor platforms to provide high-resolution bathymetric and hydrographic data collections at remote locations.

FIGURE 9

Contour map of Wild Pond, generated from bathymetry data.



A baseline characterization data set was collected during four field deployments: July 2006, August 2008, September 2008, and most recently July 2009. This sampling has provided data from a variety of tundra lakes spanning a large geographic area with some repeat sampling and specific targeted scientific investigations such as saltwater intrusion, Yellow-billed Loon habitat assessments, and temporal lake dynamics. The full data set including summary statistics, data maps, presentations, posters, and reports is available on the Tundra Lake Studies website (http://tundralakestudies.mtri.org/) (Figure 10).

Sites visited on these missions are located near Helmerick's, Deadhorse, and inside the boundaries of the Arctic National Wildlife Refuge. The team was airlifted to specific sites via helicopter with GPS and then programmed the *BathyBoat* to perform one or more tracks across the width of the lake to sample water depth, temperature, and conductivity (Figure 11). In addition to the bathymetry data for each lake, environmental sampling was conducted to characterize local habitats near the lakes in efforts to preserve many of Alaska's endangered species.

Testing continued for 10 days in 2009 as the *BathyBoat* surveyed over 14 lakes on the North Slope. The field measurements of bathymetry, temperature, and conductivity have been used in combination with electro-optical and synthetic aperture radar satellite data to create new computer algorithms that map and help predict which lakes are deep enough to harvest water for winter ice road and ice infrastructure construction, among other needs. During the Alaskan winter, most lakes freeze completely to the lake bed. To retrieve water for ice roads, teams must drill through the solid layer of ice to reach liquid water, if available. It is both costly and time consuming to deploy and position equipment and personnel at a lake to attempt water withdrawal without the guarantee of success. The new satellite algorithms are an attempt to provide detailed locations and overall

FIGURE 10

North Slope geographic information system information made available to the public by MTRI.

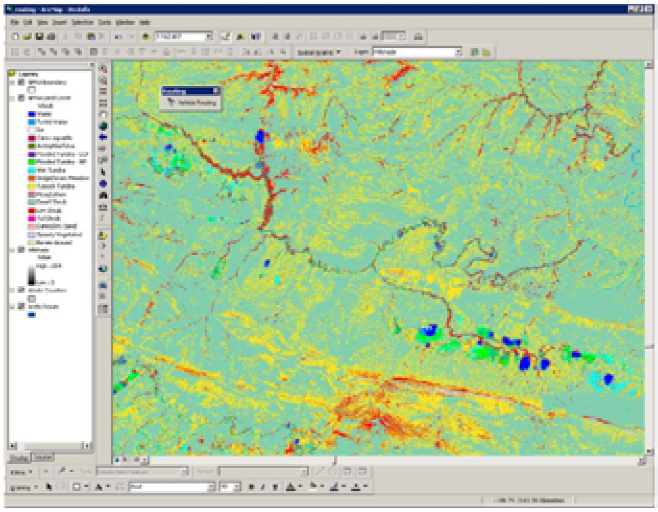
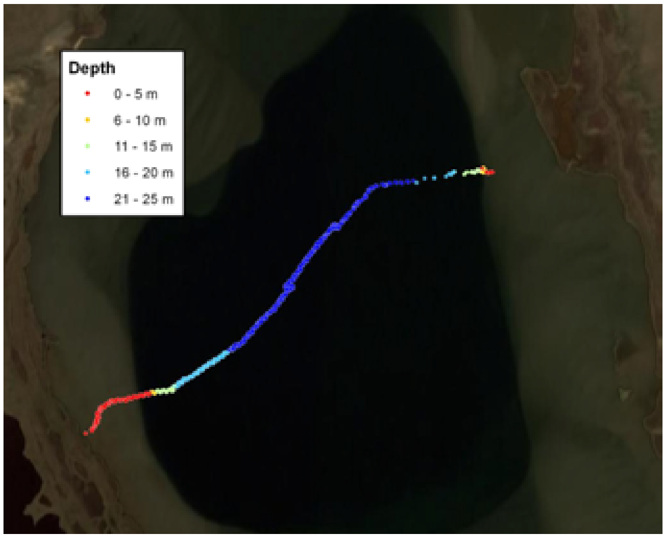


FIGURE 11

Bathymetry map of a remote lake in the Arctic National Wildlife Refuge.



descriptions of lakes, which will provide liquid water on the first attempt.

MTRI has established a comprehensive database containing all available spatial geographic information system data pertaining to the North Slope of Alaska (Figure 10) and has made it available through a Web portal to managers, planners, scientists, and the general public.

The *BathyBoat* ASV maintained 2 knots (1 m/s) and sampled at 1 Hz during this phase of testing while surveying over 7 miles of lake tracks. Post-processing of mission data resulted in Google Earth KML files, which can be downloaded and viewed by scientists around the world using the free Google Earth software. The data are geo referenced and displayed at the sample locations around the globe (as in Figure 8).

Conclusion and Future Work

As the number of autonomous vehicles exploring the world's waters expands, communication and control schemes will become paramount to performing organized and efficient missions. This article reports the research conducted at the MHL, on the subjects of (1) autonomous navigation, (2) ASV control, and (3) cooperative search. We also describe the design and construction of a new ASV, *BathyBoat*, with onboard embedded Rabbit LP3500 controller, GPS, depth sensor, and Honeywell HMR3300 digital compass. The integration of two modified *Iver2* vehicles, with the *BathyBoat*, to form a heterogeneous multivehicle network for both fresh and salt water environmental surveys was discussed. The goal of the continued work is the development of new navigation and control algorithms while streamlining the operational logistics of a complete, low-cost, underwater survey system.

Testing in Michigan, Illinois, and the North Slope of Alaska has afforded the opportunities to work in both ideal and extreme environments. These trials highlighted certain design aspects and provided insight into systems design for remote deployments. During the Harrisville Harbor study, depth sounder accuracy was measured to be within 0.1 m over subsequent sampling along a fixed geographical path. This result was well within the expected range and can be improved with a higher-resolution replacement depth sounder. A faster rate of environmental sampling, 8 versus 1 Hz, would also afford a more dense data set and therefore a more accurate model of actual conditions. This is achievable with software modifications and reimplementation on the LP3500 Rabbit Processor. On the basis of the encouraging results of field trials, the MHL is in the process of updating both control software and sensor hardware of the *BathyBoat*. These updates will be in place for upcoming missions during the summer of 2010. The missions will also involve merging SLAM software on the *Iver2* vehicles with the surface capabilities of the *BathyBoat* to enable high-precision subsea mapping as well as high-speed riverine reconnaissance.

Lead Author:

Hunter C. Brown
University of Michigan
hcbrown@umich.edu

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