Improving Autonomy and Control of Autonomous Surface Vehicles in Port Protection and Mine Countermeasure Scenarios

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Recent experimentation with autonomous surface vehicles (ASVs) has focused on the use of such platforms to perform tasks of classification or identification of objects first discovered by another sensor. The ASV generally carries small sensors capable of high-resolution imaging, but only at relatively short ranges. Reacquisition of a contact is inherent in the problem of classification and involves positioning of the surface vehicle with good precision such that the object of interest is in the field of view of the sensors aboard the ASV. This critical task of positioning the vehicle such that the classification sensors can be effectively brought to bear is the primary goal of our autonomy development. Experimental results from a variety of sensors are presented, but the most important in our present work has been a high-resolution multibeam imaging sonar operating at 450 kHz. This sensor has been successfully used to image divers and bottom objects, with telemetry data sent back to shore via wireless LAN. Although classification was done by a human operator ashore, the vehicle has the capability to keep an object in view of the sensor, representing an important operational advantage of the autonomy. Future work could expand the role of the unmanned platform to deployment of effectors—warning devices or entanglement devices in the case of harbor protection missions or neutralization devices in the case of countermine operations.

1. INTRODUCTION

The capability of operationally deployed unmanned platforms is generally limited to executing missions preplanned by an operator. In such systems, it is imperative that human operators intervene to observe events, make decisions, and guide the vehicle in achieving its mission. Although research at a few institutions has shown some ability to replan a mission on the fly (Benjamin & Curcio, 2004; Benjamin, Curcio, & Newman, 2006; Kenyon, 2009; Li, Farrell, Pang, & Arrieta, 2006), a consistent framework for such actions remains a research goal. An autonomous vehicle with a data reactive mission planner can acquire data more quickly and reliably than a fixed mission plan because the reactive planner can keep the vehicle in the vicinity of, or maneuver relative to, the interesting sensor data (Williams & Evans, 2008). Further to the autonomy and capability in mission planning, the maneuverability of present state-of-the-art vehicles is often not suited to successful autonomous accomplishment of many of the desired tasks.

This paper describes results from three collaborative experiments combining the objectives and resources from three related NATO Undersea Research Centre (NURC) projects. A common goal of all three efforts has been the employment of autonomous behaviors to reduce the workload on the operator and the overall mission timeline. What to classify and how to classify it can be viewed as the duty of the operator, whereas the mundane task of carrying the sensors to a location at which they can optimally provide the appropriate imagery is the realm of the autonomous system aboard the autonomous surface vehicle (ASV). This research was performed per requirement by Allied Command Transformation (ACT) as a combination of NURC's Scientific Programme of Work (AMCM), and ACT's Experimental Programme of Work (Contingency Capability for Port Protection and ASVs for Defence against Terrorism). The three related projects are outlined in the following paragraphs.

- As a part of its Autonomous Mine Countermeasures (AMCM) Programme, NURC is currently exploring various sea mine neutralization options. The research is based on the integration and enhancement of three technology components to derive a unique unmanned vehicle-based system in support of mine neutralization missions. These elements include NURC's ASV assets, the imaging sonar systems, and its behavior-based autonomy system. In the envisioned concept of operations, an autonomous vehicle autonomously reacquires a previously identified target using its imaging sonar(s). The vehicle then initiates an adaptive engagement plan, preferably autonomously. The vehicle tracks,

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scans, and maintains the target in the field of view (FOV) of the classification sonar, while compensating for wind, waves, and currents. Next, the vehicle guides a low-cost neutralization vehicle to deploy a payload to neutralize the target. Finally, the vehicle performs a neutralization assessment to determine and report the degree to which the mission has been accomplished.
- The objective of the contingency capability for port protection (CCPP) project was to augment a surveillance system composed of fixed sensors (surface search radar, diver detection sonar, cameras, etc.) with an ASV equipped with underwater sensors. The benefit of the ASV and its associated short-range identification sonars is that it can move into a position to identify an inbound threat, issue warnings, and observe response (compliance or noncompliance) with the warnings issued.
- The ASVs for Defence Against Terrorism (ASV for DAT) project extended this capability in two important realms—the use of ASVs was generalized to multiple vehicles, and the vehicles were equipped with surface sensors in order to respond, identify, and cooperatively maintain defensive posture against surface or subsurface threats.

The paper is organized as follows. Section 2 presents the ASV and MOOS implementation. The performance of the autonomy system exercised in a variety a tasks forming an overall mission is described in Section 3. Finally, Section 4 contains the conclusions and describes some problems that warrant further research.

2. DESCRIPTION OF EXPERIMENTS AND HARDWARE AND SOFTWARE UTILIZED

Three recent experiments at NURC have explored the set of tasks that could be performed by unmanned platforms in defense of an area around a high-value asset in a harbor or in the shallow-water approaches of a harbor. These were as follows:

- PROVEx (Practices, Operation, and Verification Experiment) in November 2008, which took place in Eckernförde, Germany
- CATHARSIS 2 in October 2009, held off the coast of the island of Elba in the Tuscan archipelago of Italy
- PROVEx09 in December 2009, held in the Gulf of La Spezia, Italy

The common thread linking the three experiments is the autonomy software with its progressive improvements and one autonomous surface vessel—a 4.7-m rigid-hulled inflatable boat (RHIB) powered by a single 20-hp outboard. The vessel's organic control system is SPECTRE autopilot (Robinson, 2008). The SPECTRE autopilot system is a subsystem that fits into a vehicle and interacts with a number of external sensors and actuators to control the vehicle. The SPECTRE autopilot comprises a processor printed circuit board (PCB), which combines analog, digital, and serial input and output interfaces, allowing it to be used for a range of data acquisition and machinery control roles. Embedded software provides a suite of autopilot algorithms, allowing SPECTRE to control machinery and actuators to reach and maintain setpoints. In addition, the SPECTRE autopilot supports external reference input through serial communication, using the NMEA 0183 standard. An external control infrastructure can utilize this option to transmit reference information to SPECTRE. Therefore, the developer-chosen control application in this framework can transmit speed, heading, or heading rate references to the SPECTRE autopilot.

Table I. Vehicles and equipment suite used in the three experiments.

	CATHARSIS	PROVEx08	PROVEx09
4.7-m RHIB ASV	X	X	X
BlueView, forward looking	X	X	X
GPS	X	X	X
Video camera	X	X	X
Orientation sensor	X	X	X
MarineSonics sidescan sonar		X	X
BlueView, side looking	X		
LMS291 laser scanner			X
4-m catamaran ASV			X
GPS			X
Video camera			X
Orientation sensor			X
LMS291 laser scanner			X

As shown in Table I, four sensors were common to all three experiments. The global positioning system (GPS), video camera, and Microstrain 3DM-GX1 three-axis orientation sensor are widely used and warrant no further discussion. The high-resolution, multibeam imaging sonar chosen for this project was the BlueView P450, operating at 450 kHz. Prior experimentation (Crawford, Crowe, Pastore, & Kessel, 2008; Kessel, Pastore, Crawford, & Crowe, 2008) has shown that although other sonars might provide more detailed imagery, the BlueView P450 represents a good balance of size (important for drag considerations), cost, and performance. Objects on the order of 2 m in length can be spotted in the display out to a maximum range of approximately 60 m and be readily classified at ranges of nearly 20 m. The BlueView P450 has a beamwidth of 1 deg and a sector width of about 45 deg. In elevation, the beamwidth is advertised at 15 deg. NURC vessels normally have the devices mounted about 20 deg below horizontal. The mount is manually adjustable prior to deployment of the vessel, so that declination angle can be chosen for the particular

Figure 1. NURC ASVs: SeaRobotics USV-2600 (left) and H-Scientific RHIB equipped with SPECTRE (right).

mission requirements and local environment (Pastore, Curcio, Fioravanti, Kessel, Robinson, et al., 2009).

For the first PROVEx in 2008, the vessel was also fitted with a sidescan sonar. The device chosen was a 600-kHz SeaKing from MarineSonics. As with the BlueView (forward-looking sonar), the MarineSonics data were fed to the shore monitoring and control station, where the data could be viewed in real time and georeferenced mosaics of the sidescan data could be constructed.

For the CATHARSIS 2 trial in 2009, the vessel was fitted with a second BlueView P450 sonar instead of the sidescan sonar. The data from both BlueView sonars were fed to the shore monitoring and control station, where they could be viewed in real time. The second sonar was mounted laterally to the hull of the ASV for the purpose of a circular target reacquisition mission. In addition, the ASV was equipped with the high-end MRU 6 motion reference unit, which was used instead of the GX1. The MRU 6 measures linear accelerations via accelerometers and angular rates via fiber-optic gyros. The data were fused within a SPECTRE board for improved vehicle navigation.

During the PROVEx09 event, a second surface vessel was added to the system. Although the two vessels were built to the same broad performance and envelope specifications (<5.5-m length, <1-m draft, <600-kg displacement, minimum payload of 40 kg and 40 liters), the two vessels are physically very different. The newer vessel is a catamaran with two electric trolling motors that provide differential thrust. This configuration enables the vessel to turn in place and execute quick bursts in reverse with fine control. These are very useful attributes for station keeping and tracking agile targets. Although lighter and smaller, it exceeds nearly all of the performance specifications given in the call for tender. See Figure 1.

The operator workstation for a harbor protection mission and MCM neutralization mission has two primary elements (see Figure 2):

1. A geographic display showing the location of the autonomous systems (generally plural) along with any other vessels tracked or cooperating in the operation. Tracked vessels are available from radar or sonar

Figure 2. Example of dual display showing geographic display (right) and ASV sensors (left).

placed at a fixed location somewhere in the port. A discussion of the details of the fusion system used in this shore-based system is outside the scope of this paper. It is relevant to realize that the cuing is supplied from a common operational picture (COP), which may represent the output of a single sensor, or automatically combined data from multiple identical or heterogeneous fixed-location sensors.

2. An "ASV sensor display," which can show any or all of the relevant sensor data from the ASVs in real time. These sensors (in our experimentation) can include the following:
   (a) high-resolution multibeam imaging sonar (one or two)
   (b) sidescan sonar (waterfall)
   (c) sidescan sonar (georeferenced mosaic)
   (d) laser scanner
   (e) video camera
   (f) dashboard display of engine status, speed, heading, pitch, etc.

The task of the operator is to focus on the contacts and tracks on the geographic display and the classification-quality sensor data on the auxiliary display. The objective of the autonomy is to seamlessly and quickly place the vessel and its sensors where they do the most good in assessing the situation at a given moment. The operator has precedence over the autonomous decisions, but his input should remain at a high level—indicating only where or what should be placed in the FOV of the classification sensors. Details of specific operator/vehicle interactions are given in the relevant sections below.

As described above, both vessels have their own control system aboard and control and monitoring station ashore. These are considered secondary to the autonomy objectives of the experiment and are generally used only to perform initial teleoperated positioning of the vessels at the start and end of the mission. More importantly, the vessels provide an interface by which NMEA commands can be sent to the organic onboard processor, allowing a second onboard processor to autonomously control the vessel. This introduces the front-seat/backseat concept of autonomous operation, wherein the vessel specific control functions are handled by a "front-seat driver" and the higher level autonomy functions are properly handled by a "backseat driver." An example for such as concept implemented onto an autonomous underwater vehicle (AUV) is given in Eickstedt and Sideleau (2009).

NURC's approach is to develop data reactive mission plans. In such an approach, the mission plan is developed onboard the vehicle in response to the sensor data. The mission plan is defined by behaviors and logic for switching among the behaviors. A "mode" is defined by a number of connected behaviors. For example, in the swimmer defense application, the ASV might start the mission in a search behavior that patrols a region until the sonar detects a moving object meeting certain sonar characteristics. After such a detection, the ASV would switch to a behavior to alert security personnel, to a tracking behavior, or to both sequentially. In either case, the ASV mission trajectory is directly determined based on sensor data.

Although there are various software architectures that allow for behavior-based planning and control (Arkin, 1987; Brooks, 1986; Huntsberger, Aghazarian, Baumgartner, & Schenker, 2000), the architecture chosen to implement the autonomous backseat driver was MOOS-IvP (Benjamin, 2004; Benjamin, Leonard, Schmidt, & Newman, 2009). This architecture was already in use on other NURC autonomous platforms, for example OEX AUV as described in a companion paper that is being submitted to this journal. MOOS is a suite of open-source software facilitating interprocess and interprocessor communication via a publish-and-subscribe paradigm. It was initially developed by Paul Newman of Oxford University. It is used extensively in the robotics community. IvP stands for Interval Programming, and the IvP-Helm is a MOOS process written and maintained by Michael Benjamin of NUWC and MIT. The IvP-Helm consists of a computationally efficient means of reducing one or more autonomy objectives to an output that can be fed to a generalized front-seat driver. In particular, the outputs of IvP-Helm are usually desired speed, desired heading, and (in the case of subsurface vessels) desired depth. In addition to commonly implemented heading control by outputting desired heading, using the MOOS-IvP framework we implemented a nonlinear controller based on a backstepping nonlinear control technique that output a desired yaw rate for more precise tracking of complex trajectories. In short, IvP-Helm can be thought of as the skipper of the autonomous vessel, with the new desired heading and speed generally supplied to the low-level control system at a rate of about four or five times per second. This architecture consists of an open-source distributed autonomy system and an approach to behavior-based control of autonomous vehicles using multiple-objective functions that allows reactive control in complex environments with multiple constraints. Whereas low-level control tasks such as navigation, depth keeping, and vehicle safety are assigned to the autonomous vehicle's main computer, all high-level control inputs are derived from a separate vehicle payload computer running the MOOS-IvP system. Our goal was to use the existing MOOS open-source features and its ability to dynamically react to its environment in order to increase the functional autonomy of the existing autonomous vehicles. Two such examples are described in the following section, where an output from a sonar sensor is used to direct the robot to change its trajectory as the new mission plan is developed onboard the vehicle in response to the sensor data for the purpose of diver detection (PROVEx08) and mine reacquisition (CATHARSIS 2). In addition, this architecture

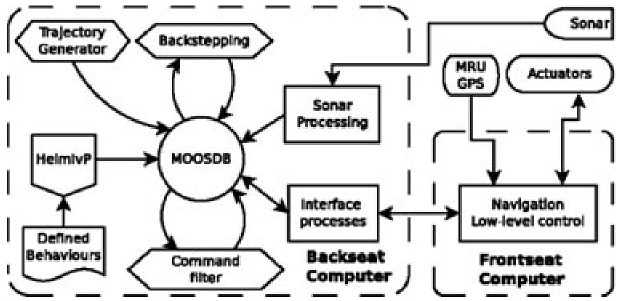

Figure 3. Process and data-flow diagram of H-Scientific RHIB as equipped for CATHARSIS trial.

enabled us to implement an advanced nonlinear controller based on Command Filtered Backstepping (CFBS) onboard the NURC's 4.7-m RHIB ASV. The program executing mission planning and control algorithms for stable trajectory tracking were interfaced with the commercial off-the-shelf (COTS) autopilot.

The front-seat/backseat control infrastructure implemented on the ASV for the CATHARSIS 2 trial is shown in Figure 3. Guidance and sonar processing are performed on the backseat computer. Access to actuators from the backseat is not allowed. Course, course rate, and speed control were performed by the front seat. MOOS processes communicate through a MOOS database in a publish–subscribe manner. Variables of interest are published to this database by the various processes; others subscribe to variables they need. Modular design is achieved this way. For example, the backstepping process uses information about the x and y vehicle position. If x and y are supplied by a different module, we could easily switch between modules that estimate x and y from navigation data without resetting the backstepping process.

The utility of MOOS extends easily beyond the application to autonomous vessels. It is used in our prototype system to pass tracks from diver-detection sonar and surface-search radar into a common operational picture.

3. TASKS FORMING THE MISSION AND RESULTS FROM EACH

Let us explore the elements and capabilities of the prototype system demonstrated in these three experiments through a logical sequence of events in a harbor defense mission and, where appropriate, in a MCM neutralization mission.

3.1. Survey

A logical first task on arrival in a protected area is to survey the area to be protected, using surface and subsurface sensors. MOOS-IvP allowed our autonomous vessels to follow an arbitrary polygon or lawn-mower pattern, streaming and recording sidescan sonar and video camera data to the shore station to provide a baseline view of the area to be protected. The important measures of performance in this task are the rate of coverage and the quality of the coverage. The rate of coverage is dictated by the sidescan sensor. Optimal speed for such a sensor is generally accepted to be about 3–4 kn (1.5–2 m/s). From a perspective of only subsurface sidescan acoustic data, the optimal parameters for the sensor are as follows:

- near the bottom
- isolated from surface motion
- in a pattern that minimizes turns

The first two constraints are easily met by an AUV, but the AUV generally does not have the ability to stream data back to a shore station in real time, especially if operating near the bottom. An additional advantage of an AUV is the variable-depth characteristic, which makes its sensor performance less affected by weather and sound speed variations. Because we were interested in a multimission platform (the ASV), we made concessions on the first two constraints and fix mounted the sidescan sonar only slightly below the keel of the RHIB. In relatively shallow water (less than 15 m) and relatively calm conditions (as found in protected harbors), acceptable sidescan images of bottom topography and conspicuous underwater objects can be obtained. The third constraint (choice of pattern and minimizing of turns) can be done equally well with an ASV or an AUV. In practice the coverage rate of the two options is similar and driven primarily by the speed normally used to transit a survey pattern. In an AUV survey, a faster speed drains valuable energy resources unnecessarily quickly. In an ASV survey, the faster speed available would only result in inferior imagery as sensor stability would suffer.

This use of autonomous systems in littoral MCM and harbor protection seeks to leverage the transformation currently underway from a Cold War legacy focused on postoperations clearance with surface ships to a quickly deployable system. The result will be a capability that is scalable to the needs of the operation and to offering an order-of-magnitude increase in the tempo of operations and reduction in through-life costs, keeping man out of the mine field. Nowdays, MCM surveys are routinely being performed by AUVs. The autonomous MCM tasks relevant to the CATHARSIS 2 experiment were those related to neutralization (see a later section) rather than detection and superclassification.

3.2. Detection (Sense and React with Operator Input)

The first form of interaction between operator and ASV is a capability first developed and shown in the PROVEx08 (Pastore et al., 2009; Pastore & Kessel, 2009). This behavior is called "drive-by" classification, and the objective is simply to get a single look with the forward-looking BlueView sonar at an object that was noted on the sidescan display. It allows the operator to click an interesting object on the waterfall display showing the sidescan data, and the vessel's course is preempted to retrace and investigate the object with the forward-looking BlueView sonar. The behavior interrupts the current pattern but does so without changing the mode of operation. The location of the point is calculated by knowing two things from the point that is clicked on the waterfall display: the time of the ping and the distance abeam of the vessel (port or starboard). When combined with the GPS information from the vessel at that past time and the heading information from the vessel, an absolute location of the click can be calculated. The ASV promptly changes course to drive to that point, slows on approach to it, and upon reaching the point (with a tolerance of about 5 m) resumes navigation (often a lawn-mower pattern or other fixed patrol) as before the click occurred.

Distinct from the drive-by classification, NURC researchers also implemented a detailed "circle and hold in view" classification behavior. This behavior set was demonstrated during the CATHARSIS 2 experiment. This demonstrated the ability of the ASV to reacquire a bottom contact specified by the operator and then maneuver relative to the contact using an ASV equipped with two BlueView sonars to perform the following trial objectives:

- investigate the possibility of reacquisition of the target with the ASV
- investigate the possibility of controlling the position of the ASV relative to the target location
- test the concept of guiding a neutralization weapon to the target based on the contact location obtained from the survey/hunting mission with accuracy currently up to 10 m

As seen in the diagram on the bottom in Figure 4, based on the data gathered from the survey mission, a small area (typically a 10×10 m box) that includes the contact is determined. While the ASV performs a "lawn-mower" behavior in this area, data from the forward-looking BlueView sonar are streamed to the operator ashore. Upon detection of a bottom contact, the operator clicks the contact of interest. As with the sidescan sensor, the clicked pixel position is then recalculated into the vehicle coordinate system, and the vehicle automatically maneuvers relative to this position. The ASV can then perform, for instance, "station-keeping while pointing at the target" or "circle and hold in view" behaviors while the side-looking sonar is imaging the target. Figure 5 shows the trajectory of the ASV performing circling behavior. The radius of the circle, determined by the distance to the target in the sonar display, can be automatically adjusted in order to obtain optimal sonar imagery as well as determine maximum sonar range. The idea behind this is to detect a potential target through sonar image processing. Currently an operator identifies the target from a sonar image and clicks on it to feed back the

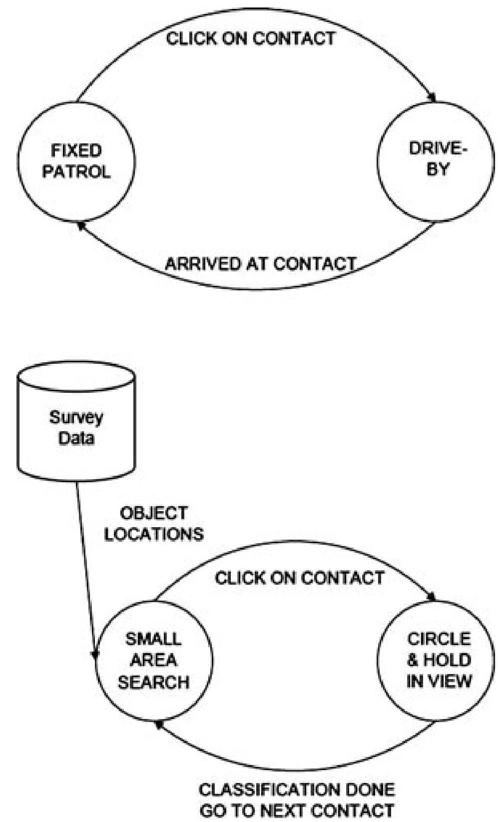

Figure 4. State diagram of drive-by classification (top) and circle and hold in view (bottom).

target position. It is obvious that with the addition of sonar image processing, this could be a fully autonomous system.

The behaviors were implemented using the same open-source software (MOOS-IvP). To compare the navigation and control vehicle performance for different behaviors, we designed the following behaviors: "circle with maintaining relative bearing to the point," "circle by controlling yaw," "circle by controlling both yaw and yaw rate," "station-keeping while pointing at the target," and "lawn-mower" behavior. The controllers that were used to implement the last four behaviors were designed using a CFBS approach (Farrell, Polycarpou, Sharma, & Dong, 2007), which was previously implemented for controlling an AUV and a land robot (Djapic, Farrell, & Dong, 2008). This nonlinear controller design is used for accurate tracking of any smooth trajectory, for example a circular trajectory.

Behavior-based control algorithms are sometimes criticized due to the lack of rigorous stability analysis. However, when each behavior is implemented as a nonlinear controller with a rigorous stability analysis, the main remaining issue is the design of behavior switching. The Lyapunov function is used as a measure of the tracking error. Stating that the Lyapunov function is nonincreasing is equivalent to stating that the tracking error decreases exponentially to zero. According to the argument in Branicky (1998), the performance using a hybrid controller is no worse than what it would be by using any single feedback function without switching. The following logic applies: *If* the Lyapunov function (a function of tracking error) is nonincreasing during each behavior *and* the Lyapunov function is nonincreasing at behavior switching instances (a hybrid system stability requirement) *then* performance using a hybrid controller is no worse than what it would be by using any single feedback function. In many cases, the performance using a hybrid controller is substantially better. Examples in which this strategy is effective include flight control, air traffic control, missile guidance, process control, and robotics. Our control architecture combines the advantages of behavior-based control (explained earlier) and Lyapunov stability (inherent in CFBS nonlinear controllers), which allows for a theoretical assessment of the stability conditions for the system. It was proven in Farrell et al. (2007) that using CFBS (a novel backstepping feedback control implementation approach), stability is achieved because the tracking error decreases exponentially to zero during each behavior as in the case of backstepping. Furthermore, the Lyapunov function is nonincreasing at behavior switching instances by choosing the appropriate initial conditions for the command filter (Djapic, 2009).

The implementation of the controller is done in the MOOS IvP-Helm framework, which allows flexibility in the control and mission planning design. The CFBS controller generates the control signals, which are inputs to the COTS autopilot enabling the control systems of the current generation of autonomous vehicles to be easily adapted or new systems rapidly designed. The control performance was verified in simulation and tested onboard the ASV.

Figure 6 shows the sonar imagery that was collected during a circular target reacquisition mission. It was demonstrated that the target can be detected and kept in the FOV of the sonar from 60 m away (maximum detectable range for BlueView P450 in these operating conditions). The circular behavior can be used to obtain the optimal sonar angle with respect to the target based on the target shape. As expected, a cylindrical target is more visible in the imagery when it is imaged broadside as seen in Figure 6. In turn, this position can be used for the "stationkeeping behavior while pointing at the target."

The environment of CATHARSIS 2 (surface waves, winds and currents, shallow water, bottom type, and bathymetry variations) demonstrated the need for greater maneuverability of the ASV. In future experiments we will consider other ASV types with finer actuator response for smoother speed and heading control (4-m catamaran shown on the left in Figure 1). In addition, we will consider the possibility for varying the depth of the sonar and adjusting the rotation and declination of the sonar FOV via a pan and tilt unit that will aid in countering environmental disturbances. By testing the developed algorithms onboard this ASV, we will gather the necessary data to determine the most appropriate reacquisition platform for various scenarios encountered in MCM. In addition, we will consider the possibility for varying the depth of the sonar and adjusting the rotation and declination of the sonar FOV via a pan and tilt unit that will aid in countering environmental disturbances. By testing the developed algorithms onboard this ASV, we will gather the necessary data to determine the most appropriate reacquisition platform for various scenarios encountered in MCM.

A practical matter in performing a survey in a new location is the presence of obstacles. The discussion of this necessary component of the system is initially restricted to fixed objects, such as buoys or jetties marking the boundaries of certain zones in the harbor. The standard suite included in IvP-Helm includes an "avoid collision" behavior. Two methods for providing the coordinates of the obstacle to be avoided were implemented and tested in the PROVEx09 trial. The first method relied on coordinates supplied by an operator for known fixed objects such as permanent mooring buoys in the harbor. Such objects are treated as a point obstacle, with a certain safety radius to be avoided. Obstacles of longer extent (piers and jetties) were initially handled by a bounding box behavior, which again relied on preprogrammed lines (not necessarily forming a closed polygon) that the vessels would avoid. This is implemented as enacting a "return to center" behavior when the distance between the vessel and any bounding line is less than a predefined threshold.

3.3. Detection (Sense and React Fully Autonomously)

Adaptive obstacle avoidance was implemented in the PROVEx09 trial using a laser scanner mounted near the bow of an ASV. The SICK LMS291 was used with a resolution of 1 deg in the forward azimuthal semicircle and a resolution of 1 cm in range out to a maximum of 81.91 m. Thus, the output of the laser scanner on each scan is a vector of 180 values (one per degree) in the range of [0...8,191] representing the number of centimeters at which the infrared laser first encounters an object of sufficient reflectance. The device is capable of rates up to 75 scans/s, but practically our software read the output at a lower rate. The scan output was clustered (contiguous returns spanning two or more degrees were treated as a single object), tracked, and placed in the MOOSDB as a new contact. The tracker was very simple, linking clusters that appear in successive updates and meet kinematic parameters of realistic speed. The FOV of the sensor is small enough that data association ambiguity was not a practical problem in our experiment. The presence of a new contact inside a predefined threshold

Figure 5. MOOS IvP-Helm display of the ASV trajectory as the radius of a circular track is increased.

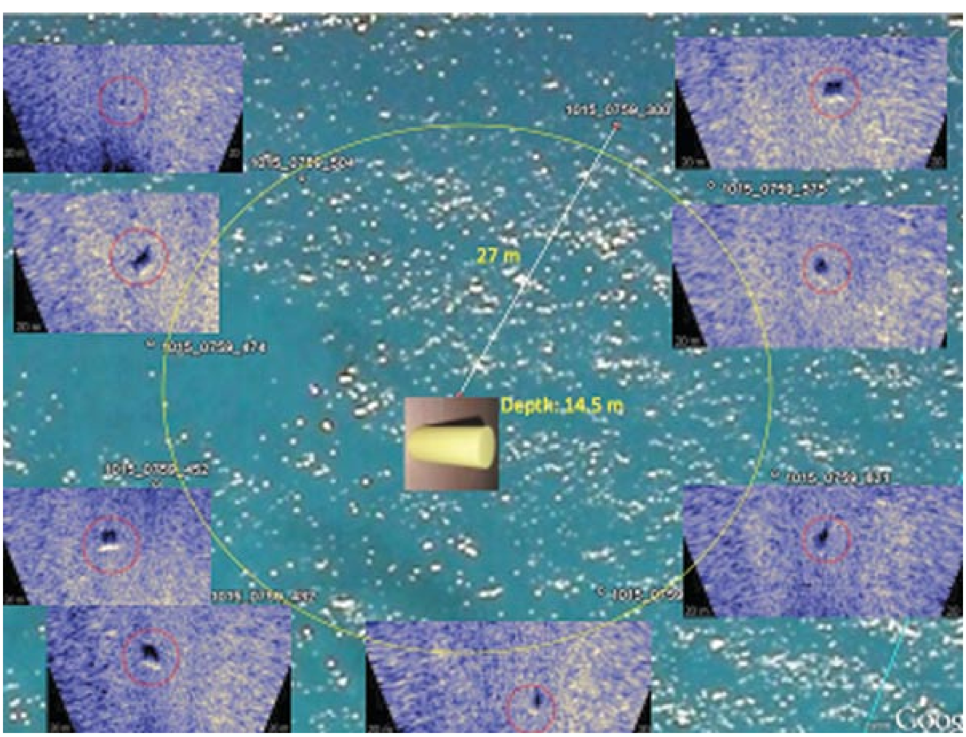

Figure 6. BlueView sonar imagery obtained while the ASV was maneuvering relative to a cylindrical target.

(typically 25 m) enabled an "avoid collision" behavior in the ASV. This capability was demonstrated to be effective in avoiding collision with stationary point obstacles (e.g., buoys), linear obstacles (piers and jetties), and moving objects (other vessels, manned or unmanned). Although the particular reaction demonstrated was to avoid the detected object, the input point could just as well be used as a point to circle around, a point to keep fixed standoff from, or any of a variety of other useful behaviors.

3.4. Classification

Our current paradigm of operation relies entirely on a human operator ashore to perform classification. The task entrusted to the autonomous vehicle is to provide the imagery necessary to do so. The location of an object to be classified can be specified by an operator directly as X–Y coordinates in a local grid or as lat/lon. Such a point may be identified by a previous survey by the same or another vehicle. As noted in Section 3.3, the location of a stationary object to be investigated can also be identified by clicking on the waterfall display of the sidescan or multibeam sonar. Once a fixed location is identified by one of these methods, the vehicle can perform the appropriate classification task—possibly driving directly toward it for viewing on the forward-looking sonar (or camera) or possibly circling it at an appropriate radius for imaging with a side-looking sensor.

A more challenging classification task has also been implemented and demonstrated—that of maintaining an appropriate position relative to a moving contact. In this case, the concurrent detection and tracking of the contact are performed by another sensor (a fixed diver-detection sonar or surface-search radar, for example). The selection of which contact to investigate and stream classification data from is done by an operator using a command and control display that unites and fuses the data from multiple detection sensors with the position of one or more ASVs published in a single MOOSDB. The steps performed by the operator are necessarily simple and can be performed very rapidly. The operator clicks on an ASV (friendly asset) to identify which vessel will be the recipient of a tasking message. The operator next clicks on a button that indicates that the nature of tasking will be to pursue another contact and with a third click identifies the contact to be pursued. Upon receipt of the message, the ASV initiates a trail behavior using preprogrammed parameters for the relative bearing and range to be maintained. Updates of position, heading, and speed from the detection sensor allow the ASV to maintain relative position and provide high-quality classification imagery. The best demonstrations of this capability are seen using the forward-looking BlueView sonar to image divers several meters below the surface of the water. A sample image from this sensor is seen in Figure 7. An extension of this behavior set has also been demonstrated to provide sidescan images of the divers (Pastore & Kessel, 2008). This was implemented by taking a position behind and to the side of the contact of interest (typically 150 deg relative and 25 m away) and then engaging a passing maneuver to a position ahead and to the side of the contact (typically 30 deg relative and 25 m away). In passing the contact, an image is formed using the sidescan sonar. These means of imaging moving objects from a moving platform constitute a key capability of our ASVs in harbor protection missions.

3.5. Neutralization

During the test in Elba in October 2009, a mine reacquisition task was implemented and demonstrated—that of maintaining an appropriate position relative to a stationary contact. In this case, the detection of the contact was performed by another sensor, a synthetic aperture sonar (SAS) onboard an AUV. The selection of which contact to investigate and reacquire was done by an operator through a postmission analysis of the SAS data. Advanced automatic target recognition (ATR) work is ongoing at NURC and elsewhere but is outside the scope of this paper. In the future, when ATR algorithms become mature, the position of the contact of interest could be passed via acoustic link to the reacquisition platform; thus the autonomous system would make an unaided decision on target detection. The mine neutralization phase is thus relying on an accurate classification and localization result from the hunting phase. In the neutralization phase, multibeam sonar imagery can be used to guide a simplified mine neutralization weapon to the moored or bottom mine. Advances in navigation, control, and sonar processing are being used to accurately determine and track the relative positions of the surface vehicle, the underwater vehicle, and the target. The overall geometric data can be used for terminal guidance and control.

During the test in Elba in October 2009, a conceptual demonstration of the mine neutralization phase was demonstrated with an ASV equipped with short-range, high-resolution sonar systems and a high-end navigation system. The goal was to investigate the possibility of reacquisition of the target with the ASV as well as to investigate the possibility of controlling the position of the ASV relative to the target location. The NURC ASV equipped with a Blueview sonar was used to mimic an autonomous mine neutralization system. It was demonstrated that the ASV can reacquire a bottom target, maintain station while pointing at the target, and perform circular search around a target while varying the circle diameter. As in the port-protection scenario, upon arrival in a protected area the first goal was to survey the area in order to reacquire a mine-like target using subsurface sensors. A lawn-mower pattern search was initiated in the vicinity of the point previously determined as a mine-like target location. Upon target detection and the operator's intervention (click to contact), the ASV initiated an appropriate behavior, namely to circle and hold in view as described in Section 3.2.

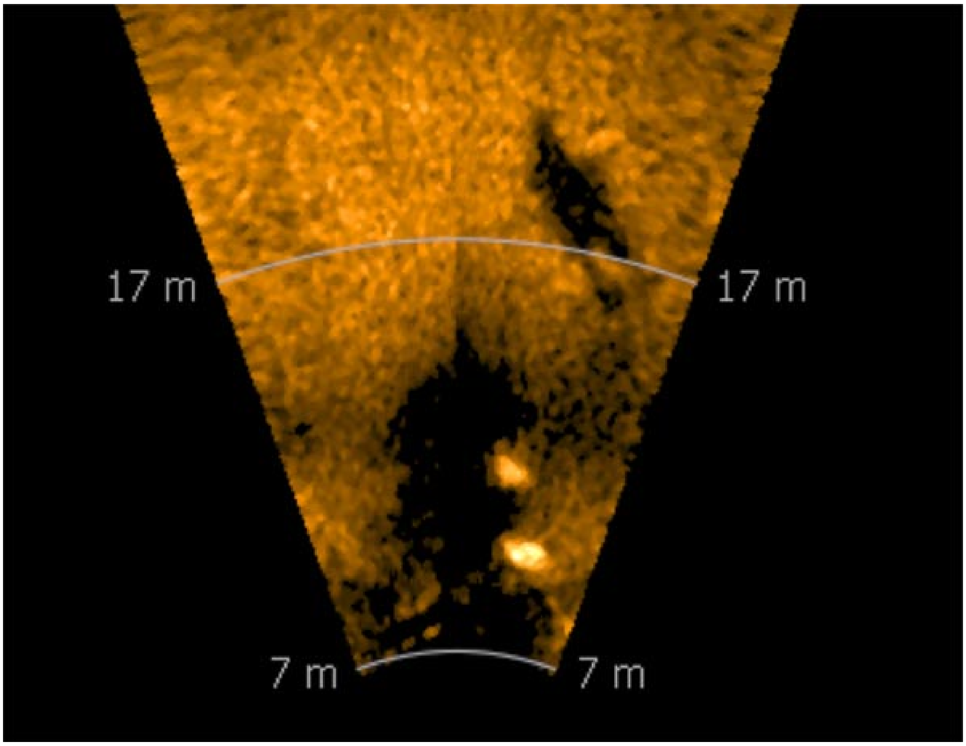

Figure 7. BlueView sonar imagery obtained while the ASV was maintaining relative position behind a pair of divers. The divers (bright) are visible in the bottom right of the frame, and the shadow appears in the upper right portion of the wedge. The shadow is often an important classification cue in such imagery.

The survey, detection, classification, and neutralization steps noted above are important building blocks. The next logical step for autonomous vessels in port protection and MCM missions is to deploy multiple (two or more) vessels in an operating area with the expectation that they will move about smartly such that they will assist rather than hinder or detract from the mission of securing the area or protecting a particular asset. Such a scenario was exercised in limited timeframes during the PROVEx09 trial. The behavior set for the "protect harbor" mission relies on a few simple behaviors and rules (Schneider, Schmidt, Pastore, & Benjamin, 2010). First, a protected asset is defined. This can be a fixed point or a moving vessel. From there, a pattern of points evenly spaced around a perimeter is defined as the stations (home positions) of the ASVs responsible for protecting the asset. There is a one-to-one correspondence between home positions and number of ASVs. In the simplest case, each ASV will loiter near its home position using minimal propulsion energy in the absence of any unknown or threatening traffic around the high-value asset (HVA). A cuing sensor (a fixed diver-detection sonar or surface-search radar, for example) will provide all ASVs with information about unidentified traffic in the area. The ASVs have a behavior attracting them to the unknown contacts in proportion to a few simple parameters: proximity to the ASV, proximity to the HVA, and closest point of approach (CPA) of the HVA if the current course is maintained. Thus, without a central command authority, the ASVs are able to maintain a simple defensive posture against inbound threats and unknown contacts, using only information that is readily available and can be passed without excessive bandwidth requirements. Explained another way, the vessels share a simplified COP. Specifically, the information required to be passed (broadcast wirelessly to all ASVs) is the position, heading, and speed of all contacts within a reasonable radius. This includes the other ASVs as well as the unidentified contacts. Thus, the number of ASVs can be inferred, and the baseline formation can be adjusted if one or more of the ASVs goes offline.

4. CONCLUSION

The PROVEx trials demonstrated repeatedly that ASVs could be tasked to pursue and provide imagery from surface and (more impressively) subsurface contacts.

Additionally, these trials demonstrated important steps toward more-automated tasking in the absence of operator input. The vessels independently determined which contacts to pursue, and this was seamlessly combined with the ability to avoid collision with such vessels, other friendly assets, and generic obstacles sensed aboard the vessel itself. Although the scope of the capability is limited to carefully designed scenarios, this meets the objective of collaborative autonomy using multiple heterogeneous vehicles.

The objective of the ASV once tasked to a particular contact is to approach it close enough that it can be identified by the human operator ashore. Secondarily (such hardware was not implemented during the trials), a warning could be issued from the ASV, clearly stating that the unknown contact has entered a restricted area. It is important to keep in mind that because the probability of a terrorist attack is very small, the ability of the ASVs to sort out and adequately deal with “false alarms” is much of the value added. However, as a next logical extrapolation, a nonlethal stopping force could be employed to bring the unauthorized vessel to a halt if an inner threshold is breached. The behaviors developed and demonstrated to follow surface and diver contacts in combination with the sense and avoid capability provided by the laser scanner at short ranges can be combined to maintain a “close, but not so close as to be dangerous” position relative to an inbound unknown contact.

Similarly, the classification and position-holding (circling a contact of interest on the seafloor) behaviors successfully demonstrated in the CATHARSIS 2 trial provide a point from which the remainder of the mission (launching a low-cost neutralization vehicle to the target, possibly assisting with terminal homing, and assessing success of the neutralization) can be extrapolated. The importance of the use of autonomous unmanned systems here extends beyond the benefit of reduced operator workload and shows a clear path for increased operator safety.

The use of autonomous systems has the potential to positively transform port protection and MCM capabilities. The demonstrated benefit of the autonomous behaviors involves minimizing the operator workload associated with the ASV. The commands appropriate for the ASV are high-level tasks such as “intercept and image a given contact.” Along the way, the vehicle remains capable of either self-directed or operator-directed retasking or interruption. Namely, the autonomy allows the vessel to avoid obstacles it might encounter, continue operating sensors that might provide contextual information to the destination contact, and remain capable of redesignation to a higher priority contact. Our prototype autonomous systems are designed to be scalable to the needs of the operation and to offer an increase in the tempo of operations and reduction of lifecycle costs. This transformation is underway today, with seabed surveys for mine detection being conducted routinely with AUVs and ASVs being considered for port protection and MCM neutralization missions. The approach and results from the three recent experiments that took the ASV capability to a higher level were described in this article.

An incremental approach with frequent in-water testing is shown for the development of an ASV system with improved autonomy and control. Only recently have advances in autonomous vehicle navigation, control, and sensor processing enabled significant improvements in the speed, capability, and risk reduction of autonomous missions. NURC’s research is based on the integration and enhancement of three component technologies to create a unique autonomous vehicle–based system. These components include an inventory of autonomous vehicles, imaging sonar systems, and open-source, cooperative behavior-based control software.

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