Using Collaborative Autonomous Vehicles in Mine Countermeasures

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***Abstract*— This article describes concepts evaluated at NATO Undersea Research Centre (NURC) recent experiment as the part of Autonomous Mine Countermeasures (MCM) Program. We investigated the possibility of reacquisition of the target with the Autonomous Surface Vehicle (ASV), the possibility of controlling the position of the ASV relative to the target location, and tested the concept of guiding a neutralization weapon to the target based on the contact location obtained from the hunting mission performed by an Autonomous Underwater Vehicle (AUV). Second part of the article focuses on implementation in the open-source MOOS-IvP software framework. This framework allows for flexibility in control and mission planning. Guidance is covered by the MOOS-IvP implementation of the controller while the COTS autopilot handles low-level control. The control performance is verified in simulation and confirms arbitrarily small tracking error as well as tested in real, at-sea environment which included external disturbances, such as currents and waves. This experiment has shown that the collaborative use of autonomous systems has the potential to transform MCM capability, from a Cold War legacy focused on post-operations clearance with surface ships, to a quickly deployable system, autonomous system.**

I. Introduction

The state of the art of the ability of autonomous unmanned platforms is currently limited to executing missions pre-planned by an operator. Thereafter, human operators must intervene to observe events, make decisions and guide the vehicle in achieving its mission. In addition, present state-of-art vehicles are often not manoeuvrable enough to successfully accomplish most of the desired autonomous tasks. Although various tools are currently available for constructing fixed mission plans, there are limited tools available to facilitate the design of reactive mission plans. Instead, each scientist or military operator who wishes to implement a data reactive plan must work with the vehicle manufacturer to develop a custom solution. That effort may be prohibitive in terms of time, cost, or effort to scientists or military operators who are unfamiliar with autonomous vehicle planning, guidance, and control. To achieve real autonomy, a data reactive mission plans must be developed which means that 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. An autonomous vehicle with a data reactive mission planner can acquire data more quickly and reliably than a fixed mission plan since the reactive planner can keep the vehicle in the vicinity of, or manoeuvre relative to, the interesting sensor data.

Autonomous Vehicles are being considered, for example, for the following maritime security missions: Mine Countermeasures (MCM), Anti-Submarine Warfare (ASW), and Port Protection (PP). Applicable threats include bottom and moored mines, mines or improvised explosive devices placed on pilings, quays, or hulls of ships at anchor or in port. Autonomous vehicles in this context include autonomous surface vehicles (ASV) and autonomous underwater vehicles (AUV). Only recently have advances in autonomous vehicle navigation, control, and sensor processing enabled significant improvements in the speed, capability and risk-reduction of, for example, mine hunting missions. These missions can be broken in mine detection and super classification mission, followed by mine neutralization mission. This article focuses on the ladder.

The researchers at the Mobile Robotics Research Group at Oxford University, the Computer Science and Artificial Intelligence Lab and Dept. of Mechanical Eng. at MIT, and the Naval Undersea Warfare Center in Newport Rhode Island (NUWC-NPT) have developed the MOOS-IvP Autonomy Architecture [3], [4]. MOOS stands for "Mission Oriented Operating Suite", and IvP stands for "Interval Programming". This architecture consists of an open-source distributed autonomy architecture and an approach to behavior based control of autonomous vehicles that allows reactive control in complex environments with multiple constraints. Low-level control tasks such as navigation, depth keeping and vehicle safety are assigned to the AUV main vehicle computer, all high-level control inputs are derived from a separate vehicle payload computer running the MIT MOOS-IvP system. Our goal is 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. One such an example is described in Sections IV and V 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. In addition, this architecture enabled us to implement an advanced nonlinear controller based on command filtered backstepping (CFBS) onboard of

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the NURC's Mandarina ASV. The program executing mission planning and control algorithms for stable trajectory tracking is interfaced with the COTS autopilot SPECTRE made by H-Scientific Ltd. [10].

The paper is organized as follows. Section II introduces the potential of using collaborative autonomous vehicles in mine countermeasures (MCM) scenarios. Section III briefly explains detection and super classification phase of MCM mission. One of the envisioned Concept of Operations (CONOPS) and performance of the autonomy system exercised in a variety a tasks in the last phase of MCM - neutralization is described in Section IV. Section V present the ASV and MOOS implementation used in the initial experimentation performed as proof-of-concept for neutralization. Finally, Section VI contains the conclusions and describes some problems that warrant further research.

II. Collaborative Autonomous Vehicles

The collaborative use of autonomous systems has the potential to transform MCM capability, from a Cold War legacy focused on post-operations clearance with surface ships, to a quickly deployable system. It is designed to be scalable to the needs of the operation and to offer an order of magnitude increase in the tempo of operations and reduction in through-life costs keeping man out of the mine field. The demonstrated benefits of the autonomous behaviors involves minimizing the operator workload associated with the autonomous platforms. This transformation is underway today, with seabed surveys for mine detection being conducted routinely with AUVs and ASVs being considered for MCM deployment and neutralization missions. As pointed out earlier, commercial-of-the-shelf (COTS) autonomous systems are equipped with tools for generating and executing a priori mission plans. Prior to sending the vehicle on a mission, the user constructs a list of mission activities. Once the mission is initiated, the mission planner sequentially completes each activity on the mission list while recording the sensor data. The data is analyzed by the operator after the vehicle is retrieved. Our research strives to design autonomous systems with data reactive mission planner utilizing open-architecture software and hardware principles. For example, in the swimmer defence 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 might switch to a behavior to alert security personnel, to a tracking behavior, or do both sequentially. In either case, the ASV mission trajectory is directly determined based on sensor data. In any point of the patrol mission the ASV can task its collaboration AUV to perform a close up identification or intervention. The commands appropriate for the ASV or AUV 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. 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.

In surveillance and reconnaissance of objects of interest in the sea, sophisticated methods have been developed for detection, classification, localization and identification. However, performing these functions reliably on objects embedded in complex, transient, cluttered environments has proven to be challenging. False alarm rates remain stubbornly high. If the end-state is intervention and all the intervention options are costly or irreversible then identification accuracy is quite demanding. Such demands can be counter-productive if the false alarm rate tracks with the probability of detection. If the process of detection through neutralization is treated as a fully coupled integrated system then a number favorable trade-offs emerge from creating end-state of (intervention) options. For example, low cost and non-lethal intervention methods may considerably relax accuracy demands and provide flexibility for the responder. Driving or optimizing from the end-state is one way to approach the development of cost-effective surveillance and reconnaissance systems that are practical and have utility in real maritime environments. This approach is being pursued at NURC for a number of missions including sea mine counter-measures.

The NURC is exploring various MCM approaches using squads of autonomous vehicles. A squad is a small group of vehicles with complementary capabilities that most effectively achieve a mission through cooperative behavior. The simplest squad consists of two vehicles. Current efforts focus on cost-effective neutralization (end-state driver) using a pair of autonomous platforms: a highly capable super-classification autonomous surface and/or underwater vehicle and a low-cost, guided neutralization autonomous underwater vehicle. Therefore, the next logical step for vessels in 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 be an asset to the authority responsible for securing the area or protecting a particular asset. In this paper, an incremental approach with frequent in-water testing is shown for the development of a ASV system with improved autonomy and control. This approach is scalable and can be applied to other autonomous platforms.

III. Detection and Super-classification

A logical first task on arrival in a protected area is to survey the area to be protected, using surface and subsurface sensors. Open-source software (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 or synthetic aperture sonar (SAS) sensor. Optimal speed for such a sensor is generally accepted to be about 3-4 knots (1.5 to 2 m/sec). From a perspective of only subsurface sidescan/SAS acoustic data, the optimal parameters for the sensor are:

1) near the bottom,
2) isolated from surface motion,

3) 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. Since we were interested in a multi-mission platform (the ASV) we made concessions on the first two constraints and fixed mounted the sidescan sonar only slightly below the keel of the ASV. In relatively shallow water (less than 15 meters) 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 ASV or AUV. In practice the coverage rate of the two options is similar, and driven primarily 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. A clear advantage of AUVs is the variable depth characteristic, which makes its sensor performance less affected by weather and sound speed variations. The autonomous MCM missions can be broken in mine detection and super-classification mission, followed by mine neutralization mission. This article focuses on the latter and therefore assumes that the survey is done earlier by an AUV.

Super classification is defined as the ability to recognize mines at long range with sufficient confidence to proceed to mine neutralization. The super classification, because it is performed with an enhanced classification system, will also provide improvement in the maximum achievable clearance rate. Typical super classification image is shown in Figure 2. Figure 1 shows a graphical depiction of a ASV and an AUV with super classification capability working together to locate and identify a mine. The super classification approach based on 3D reconstruction techniques and multiple target look using wideband synthetic aperture sonar (SAS) is described in the companion paper which is being submitted ("False-alarm reduction in mine classification using multiple looks from a synthetic aperture sonar" by J. Groen, E. Coiras and D.P. Williams).

A mine reacquisition task has been implemented and demonstrated - that of maintaining an appropriate position relative to a stationary contact. In this case, the concurrent detection and classification of the contact are performed by another sensor (SAS onboard of AUV for example). The selection of which contact to investigate and reacquire is done by an operator through a post-mission analysis of SAS data. In future, when Automatic Target Recognition (ATR) algorithms become mature the "address"-positional info of the interesting target can be passed via acoustic link to the reacquisition platform. Thus, the mine neutralization phase is relying on an accurate classification and localization result from the hunting phase. Following that phase, the lower resolution sonar feedback can be used for guiding a simplified mine neutralization weapon the moored or bottom mine since the mine has already been detected and classified with the super classification sonar. 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. This geometry is used for terminal guidance and control.

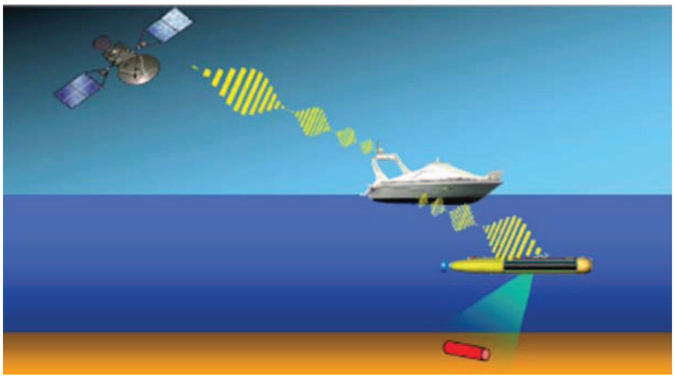

Fig. 1. Graphical depiction of a ASV and an AUV with super classification capability working together to locate and identify a mine.

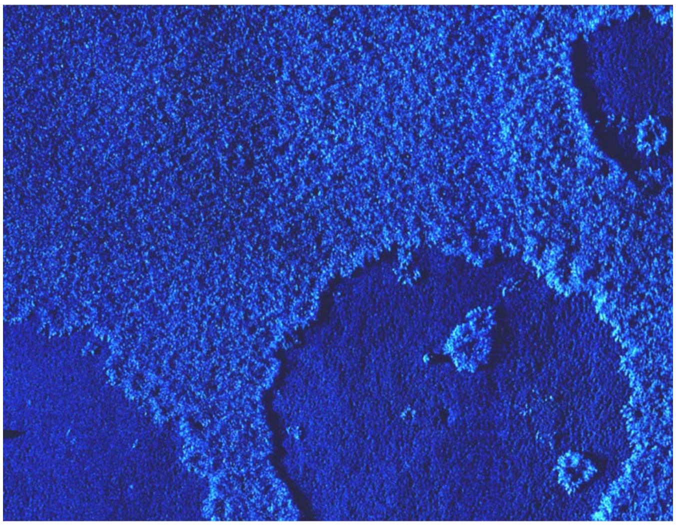

Fig. 2. SAS image of about 80 m by 40 m with two realistic target shapes on sand patches in the middle of abundant seaweed fields.

IV. Neutralization

NURC's research is based on the integration and enhancement of three component technologies to create a unique autonomous vehicle-based system for mine neutralization. These components include an inventory of autonomous vehicles, imaging sonar systems, and open-source, cooperative behavior based control software. An expendable, neutralization vehicle utilizing commercial-off-the-shelf components is being designed and non-explosive means for neutralization are being evaluated.

A. *Neutralization CONOPS*

In the envisioned concept of operations, an autonomous vehicle autonomously reacquires a previously identified target

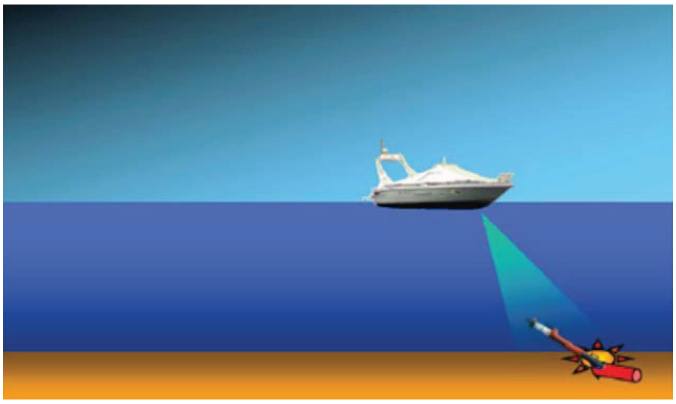

Fig. 3. A non-disposable ASV guides a disposable neutralization AUV.

Fig. 4. NURC ASVs: SeaRobotics USV-2600 (left) and h-Scientific RHIB equipped with SPECTRE (right).

using its imaging sonar(s). The vehicle then initiates an adaptive engagement plan autonomously or it may be controlled by an operator. The vehicle tracks, scans and maintains the target in the field of view 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. This concept is shown in Figure 3. Thus, an ASV with the imaging sonar is also being considered as the delivery and guiding platform for the mine-neutralization vehicle. Collaboration between the highly capable ASV and the low-cost, hence less capable, mine mine-neutralization AUV is viewed as an essential element of reliable mine neutralization.

B. Technologies Considered for Neutralization

One autonomous surface vessel was common to all of these experiments - a 4.7-meter RHIB powered by a single 20-HP outboard shown on the right in Figure 4 taken by Arjan Vermeij. The vessel's organic control system is SPECTRE autopilot [10]. The SPECTRE Autopilot System is a subsystem which fits into a vehicle, and interacts with a number of external sensors and actuators to control the vehicle. The SPECTRE Autopilot comprises a Processor PCB, which combines analogue, 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 the SPECTRE to control machinery and actuators to reach and maintain setpoints. In addition, 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. The navigation sensors onboard our ASV configured for this experiment included a motion reference unit (MRU) and GPS. MRU measures linear accelerations via accelerometers and angular rates via fiber-optic gyros. The data is fused within a SPECTRE board for vehicle navigation.

The forward looking sonar chosen for this project was the BlueView P450, operating at 450 kHz. Prior experimentation [11], [12] has shown that while 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 meters length can be spotted in the display out to 40 to 60 meters, and readily classified at ranges of nearly 20 meters. The BlueView has beamwidth of 1°, and a sector width of about 40°. In elevation, the beamwidth is advertised at 15°. NURC vessels normally have the devices mounted about 20° below horizontal. The mount is adjustable, so that declination angle can be adjusted for the particular mission requirements and local environment. For the CATHARSIS 2 sea trial we added the second P450 unit and mounted it to the side of the vessel (laterally) for the purpose of demonstration ASV circular search maneuver.

C. Initial Neutralization Demonstration

During the CATHARSIS 2 sea trial (Oct. 2009 in Elba) we successfully tested the interaction between Operator and ASV. It allows the operator to click an interesting object on the display showing the BlueView data, and the vessels course is pre-empted to retrace and investigate the object with the forward-looking BlueView sonar or side-looking BlueView sonar. The location of the point is calculated by knowing two things from the point which 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 while maneuvering relative to the bottom target. Thus, we implemented necessary control behaviors for reacquisition of the bottom target, as well as, target relative maneuvering using an ASV equipped with the multi-beam BlueView sonar.

Using the open source software we designed the behaviors which enabled target relative manoeuvring. The ASV manoeuvred in a circular fashion varying its radius with respect to the center (target location) upon operator's detection of the target in the sonar (mounted laterally) screen. It was demonstrated

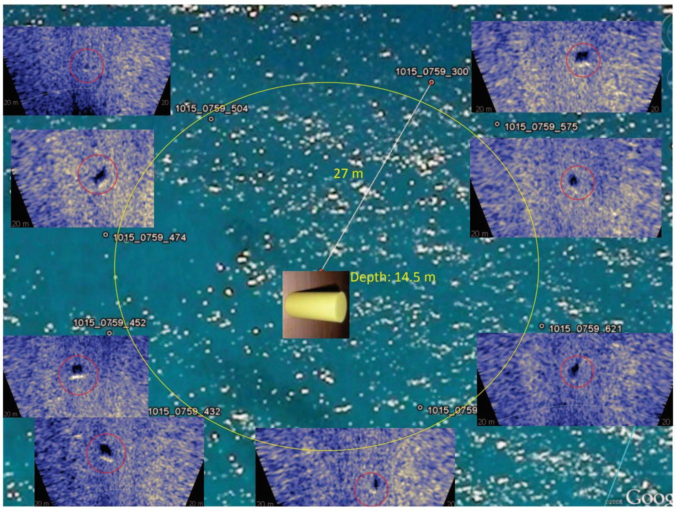

Fig. 5. BlueView sonar imagery obtained while the ASV was manoeuvring relative to a cylindrical target.

that the target can be detected and kept in the FOV of the sonar from 60 meters away. This lower resolution sonar feedback can be used for guiding a simplified mine neutralization weapon to the moored or bottom mine since the mine has already been detected and classified during the prior super classification mission. A conceptual demonstration of 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 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. The first goal is to quickly survey the area in order to reacquire a mine-like target using surface subsurface sensors. A lawn-mower pattern search is initiated around the point previously determine as a mine-like target location. The duration of the survey is dependent of the accuracy of the positional target information (its "address") obtained from the hunting phase of the MCM. Upon target detection and the operator's intervention (click-to-contact) the ASV initiated an appropriate behavior.

V. Software Implementation

Although there are various software architectures that allow for behavior based planning and control [1], [2], [9], the architecture chosen to implement the autonomous ASV was MOOS-IvP [3], [4]. This architecture was already finding use in other NURC autonomous platforms, for example OEX AUV and Mandarina ASV. MOOS is a suite of open-source software facilitating interprocess and interprocessor communication via a publish and subscribe paradigm. The IvP-Helm consists of a computationally efficient means of reducing one or more autonomy objectives to an output which can be fed to a generalized frontseat driver. In particular, the output of IvP-Helm are usually desired speed, desired heading, and (in the case of sub-surface vessels) desired depth. In addition, we implemented a non-linear controller based on backstepping as a backseat driver which outputted desired yaw-rate for more precise tracking of complex trajectories.

A. *MOOS-IvP Architecture*

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 4 or 5 times per second. This architecture consists of an open-source distributed autonomy architecture and an approach to behavior based control of autonomous vehicles using multiple objective functions that allows reactive control in complex environments with multiple constraints. While low-level control tasks such as navigation, depth keeping and vehicle safety are assigned to the ASV main vehicle computer, all high-level control inputs are derived from a separate vehicle payload computer running the MIT MOOS-IvP system. The program executing mission planning and control algorithms for stable trajectory tracking is interfaced with the COTS autopilot. 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. An example is shown 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 mine reacquisition in CATHARSIS 2. In addition, this architecture enabled us to implement an advanced nonlinear controller based on command filtered backstepping (CFBS) [5], [6], [7], [8] algorithm onboard of the NURC's Mandarina ASV. Frontseat/Backseat control infrastructure is shown in Figure 6. Guidance and sonar processing is performed on the backseat computer. Access to actuators from the backseat is not allowed. Course, course rate and speed control will be performed by the frontseat. MOOS processes communicate through a MOOS database in a publish-subscribe manner. Variables of interest are published to this database by processes, while others subscribe to variables they need. Modular design is achieved this way. For example, backstepping process uses information about x and y vehicle position. x and y is supplied by a different module. We could easily switch between modules that estimates x and y from navigation data without resetting the backstepping process.

B. *Behaviors Implemented*

Using this open source software we designed the following behaviors: "simple circle via maintaining relative bearing to the point", "circle by following the desired trajectory via backstepping nonlinear control technique", "circle by controlling both yaw and yaw rate", "keeping the desired distance to the point", and "mowing the lawn behavior". The controllers are designed using a command filtered backstepping (CFBS)

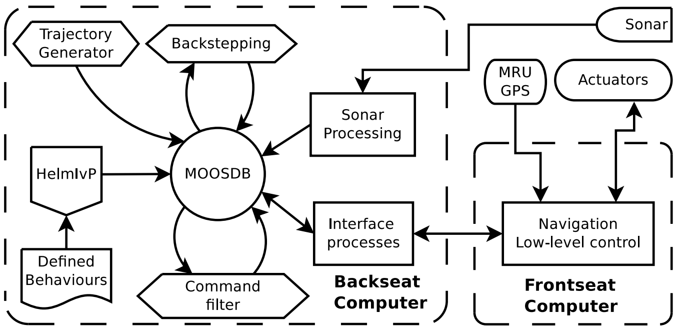

Fig. 6. Block diagram of the control system implemented on the Mandarina ASV.

approach [5], [6], which was previously implemented for controlling a land robot and an AUV [7], [8]. This nonlinear controller design is used for accurate tracking of a complex trajectory, for example a circular trajectory. Behavior-Based Control algorithms are criticized due to the lack of rigorous stability analysis. However, our each behavior is implemented as a nonlinear controller with a rigorous stability analysis. Our control architecture combines the advantages of Behavior-Based Control and Lyapunov stability since at the same time allows for a theoretical study of the stability conditions for the system. The implementation of the controller is done in MOOS IvP-Helm framework which allows the flexibility in the control and mission planning design. The CFBS controller generates the control signals which are inputs to the COTS autopilot enabling that the control systems of the current generation of autonomous vehicles can be easily adapted or new systems rapidly designed. The control performance was first verified in simulation and then tested onboard of the ASV.

While the ASV performs a mowing the lawn behavior, upon the bottom target detection, an operator is expected to identify the target from the sonar (forward-looking) image and click on it. A clicked pixel position is then recalculated into the vehicle coordinate system the vehicle automatically maneuvers relative to this position. The ASV can then perform, for instance, "station-keeping while pointing at the target" or "circling around the target" behaviors while the side-looking sonar is imaging the target. Figure 7 shows the trajectory of the ASV performing circling behavior obtained during our at-sea test. The radius of the circle, determined by the distance to the target in sonar display, can be adjusted in order to obtain optimal sonar imagery. 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 target position. It is obvious that with addition of sonar image processing this could be a fully autonomous system as described above. Figure 5 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 field-of-view (FOV) of the sonar up to 60 meters away. The circular behavior can be used to obtain the optimal sonar angle with the respect to the target based on the target shape. As expected, a cylindrical target is more visible in the imagery when the sonar is imaging broadside of the target as seen in Figure 5. In turn, this position can be used for the station-keeping behavior while pointing at the target.

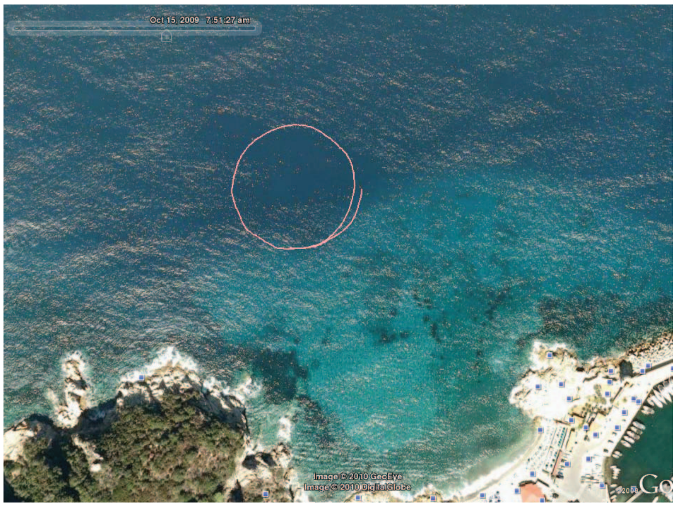

Fig. 7. MOOS-IvP Helm display of the ASV trajectory as the radius of a circular track is increased

Again, for the mine neutralization mission, as the automatic sonar image processing algorithms are being more mature they will be considered to make a decision on target detection instead of the operator during the target reacquisition phase.

VI. Conclusion

This paper describes results which show potential for collaborative use of autonomous vehicle in MCM. A common goal has been the employment of autonomous vehicle executing autonomous behaviors to minimize the workload on the operator. What to classify and how to classify it can be viewed as the duty of the operator (for now), while 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 board the ASV. The experimentation during the CATHARSIS 2 with Autonomous Surface Vehicle (ASV) focused on the use of such platform to perform tasks of reacquisition of objects first discovered by another sensor in this case MUSCLE AUV SAS system. 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 was the primary goal of our autonomy development. Experimental results from two BlueView P 450, multi-beam sonar operating at 450 kHz, are presented. This sensor has been successfully used to image divers and bottom objects, with telemetry data sent back to shore via wireless LAN. Although the vehicle has capability to keep an object in view of the sensor, present work is based on the classification done by a human operator ashore. Future work will expand the role of the autonomous platform to deployment of effectors - neutralization devices in the case of MCM operations.

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

Similarly, the classification and position-holding (circling a contact of interest on the sea floor) behaviours 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.

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