Novel method for underwater navigation aiding using a companion underwater robot as a guiding platforms

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Abstract— **This paper presents the results of multi-national collaboration during the sea trial held in the coastal waters of La Spezia, Italy, in the period 17 Oct. – 07 Nov. 2012. The trial was performed as one of the objectives of the program which has a goal to achieve the entire chain of Mine Countermeasures (MCM) using unmanned, robotic platforms. The focus of activities in this sea trial was to perform the last events of the mission: reacquisition, identification and intervention using a pair of collaborating underwater vehicles. The trial's objectives were to combine the expertise and robotic systems from different partners and achieve a mission of precise guiding of an inexpensive underwater vehicle to an underwater target using the navigation suite and control system of a more capable underwater vehicle. The objectives were accomplished and the researchers' opinion is that the extension to multi-vehicle cooperation (one leader guiding several agents, or followers) is feasible given the test results.**

I. Introduction

Most modern autonomous underwater vehicles (AUVs) provide an aided inertial system (AINS) as their navigation solution. AINS systems are based around inertial measurement unit (IMU) aided by a Doppler velocity log (DVL), depth sensor and underwater or global positioning system [1]. Aiding sensors are needed to reduce the drift rate or periodically reset position estimates. Modern INS systems are specified as being capable of heading drift rates of less than 0.01 deg/hr [2]. High accuracy comes with higher cost, which is acceptable for non-expendable AUVs, but is not desired for expendable (one-shot) unmanned underwater vehicles (UUVs), which are taken into consideration in this paper. Although the cost factor eliminates the complete AINS solution from the equation, a basic sensor suite, e.g. compass and pressure sensor, remains as a minimal requirement.

The main objective of the proposed system is for the UUV to follow a 3D path, therefore the basic sensor suite needs to be expanded with position measurements. Higher frequency long baseline (LBL) systems can offer sub-centimeter precision and update rates up to 10 Hz [3]. However, precise mooring of LBL transponders is required. Alternatively, GPS intelligent buoy (GIB) systems offer adequate performance without the need for transponders to be precisely moored on the sea-floor [4]. On the other hand, transponder deployment and recovery is still necessary. This issue can be resolved by using an ultra short baseline (USBL) system on a support platform. The downside of a USBL system is performance degradation with higher elevation angle, especially noticeable in shallow waters.

This paper presents our ongoing research and the results from recent sea trial of using a multibeam imaging sonar instead of LBL/USBL systems for the purpose of UUV navigation aiding. From the sonar image, UUV range and bearing relative to the sonar head can be measured, similarly to a USBL system. However, higher multibeam resolution offers better precision in comparison to USBL measurements. The downside is that the UUV has to remain in the sonar beam. This can be solved by mounting a sonar on a pan and tilt system or mounting it on a robot that can control all six degrees of freedom (DOF): translation in and rotation about three perpendicular axes. With our approach, a mine intervention UUV can be small and inexpensive with a basic sensor suite and an acoustic receiver for receiving measurement updates obtained from the sonar image. In addition, the paper advocates the potential of using collaborative autonomous vehicles in MCM scenarios. In the envisioned concept of operations, an AxV (surface or underwater) reacquires a mine-looking target using its imaging sonar. Immediately following, the AxV guides a low-cost mine intervention UUV carrying a payload to neutralize the target. Collaboration between the highly capable AxV and the low-cost, hence less capable, mine neutralization UUV is viewed as an interesting research subject in the field of mine reacquisition and neutralization since it can potentially drastically reduce the overall MCM mission timeline.

The paper is organized as follows. Section II introduces the potential of using collaborative autonomous vehicles in mine countermeasures (MCM) scenarios and explains the system of unmanned platforms that can be used in the intervention phase of the MCM mission. The software integration between the Latis ROV and the autonomous guiding system is described in Section III. Section IV present the sonar integration via MOOS (Cross Platform Software for Robotics Research) implementation. Section V presents the results of our recent sea trial. Finally, Section VI contains the conclusions and potential impact of this work.

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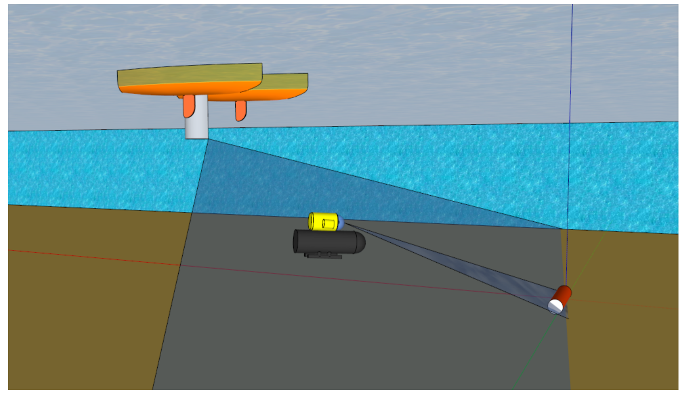
II. SYSTEM OF COOPERATIVE MARITIME VEHICLES

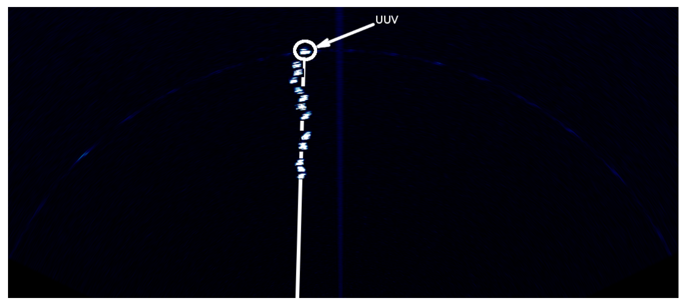
The state-of-the-art would seem to suggest that all the above-mentioned on-board sensors are necessary for accurate underwater navigation with bounded positional error, if all the robots were working independently. In such a scenario, such a highly capable suite of required on-board sensors (or in-water transponder placement operations) not only increases the cost of the individual robots and the total cost of meaningful operations, but also increases their footprint, leaving very little room for user-desired and user-defined payload modules, assuming the constraint that each individual robot continue to be a one- or two-man portable, lightweight ($\sim$ 50 kg) flexibly fieldable system. We propose, instead, to have the UUVs work cooperatively, since their cooperation will allow for a reduction of the navigation-related footprint by leveraging state-of-the-art cooperative navigation algorithms, which Centre for Maritime Research and Experimentation (CMRE) and University of Zagreb (UNIZG) have already developed through existing collaboration.

The CMRE 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 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, the development of a Smart ROV / UUV system with improved autonomy and control. This approach is scalable and can be applied to other autonomous platforms. The Mobile & Marine Robotics Research Centre, Univ. of Limerick has offered to contribute to the trial by bringing a capable, automated Remotely Operated Vehicle rated to 1500 m depth and a forward looking sonar that has a range beyond that of the same type of sonar available at CMRE. The suggested teaming can demonstrate delivery of a mine intervention vehicle to targets at significant depths and with stand-off distances longer than CMRE can demonstrate with its assets. This should help convince the operational community of the effectiveness of the concept.

The concept of external system guidance proven at CMRE has involved the autonomous surface vehicle (ASV) reacquiring a bottom target using high-resolution forward-looking imaging sonar, and guiding the delivery vehicle to close proximity of the target with minimal navigation correction information (40 bits) sent via simplified acoustic modem every 1-2 sec, (Fig. 1(a)). These corrections, that include the range and bearing to the UUV, are determined using sonar image processing, (Fig. 1(b)). The proven idea, tested at three major NATO sea trials, is that the inexpensive unmanned underwater vehicle (UUV) can be aided by a more capable surface platform [5]. In this trial this idea has been extended to 3D using an underwater robot as a guiding platform.



(a) Multibeam sonar guiding



(b) Multibeam sonar imagery

Fig. 1. External Guiding System

A. *Smart ROV Latis*

A smart Remotely Operated Vehicle, ROV Latis, is a prototype platform to test and validate OceanRINGS - a suit of smart technologies for subsea operations, developed at Mobile & Marine Robotics Research Centre, University of Limerick. It is a next generation smart ROV with unique features, including multiple modes of operation, advanced 2D and 3D displays, intuitive, versatile and easy to use pilot interface and built-in fault-tolerant control system. With integrated state-of-the-art navigation sensors/instruments, the vehicle can achieve precision navigation and subsea positioning. Other features include ROV DP in absolute earth-fixed frame or relative to ship, high precision, robust speed/course controller with independent heading control and improved ROV – ship link. ROV Latis was designed as a prototype test bed for challenging operation environments in the ocean. ROV Latis shares much with other state of the art ROVs as used in ocean engineering and ocean research. The vehicle also has many features not available in commercial ocean ROV technology [6]. With state of the art navigation sensors/instruments the vehicle can achieve precision navigation and positioning sub sea. The navigation sensor suite includes a fiber optic gyro based inertial navigation system with extended Kalman filter integrated with aiding sensors (DGPS while on the surface, ultra short base line acoustic positioning (USBL), Doppler velocity log (DVL), precision depth sensor). Such a suite of sensors, while not ubiquitous, is not uncommon on research or some work-class ROVs. The automatic control functionality and autopilot control systems developed and trialed on ROV Latis are, however, superior to systems provided on other ROVs.

1) Features: The main features of ROV Latis are:

- Modular design with multiple modes of operation,
- Very high positioning accuracy of ROV in deep water,
- Semi-Automatic Speed Modes enable robust, stable and accurate ROV Course Following & ROV Dynamic Positioning with simple mouse click,
- Fully automatic way points navigation with auto-compensation of ocean currents and umbilical drag effects,
- Advanced 2D and 3D real-time visualisation – providing better situation awareness,
- Built-in thruster fault tolerance and optimal control allocation for any thruster configuration,
- Built-in auto-tuning of low-level controllers, providing optimal controller performance, regardless of changes in ROV configuration between missions,
- Modular software architecture and extensive interface library enable easy system adaptation to any ROV - ship combination in the market.

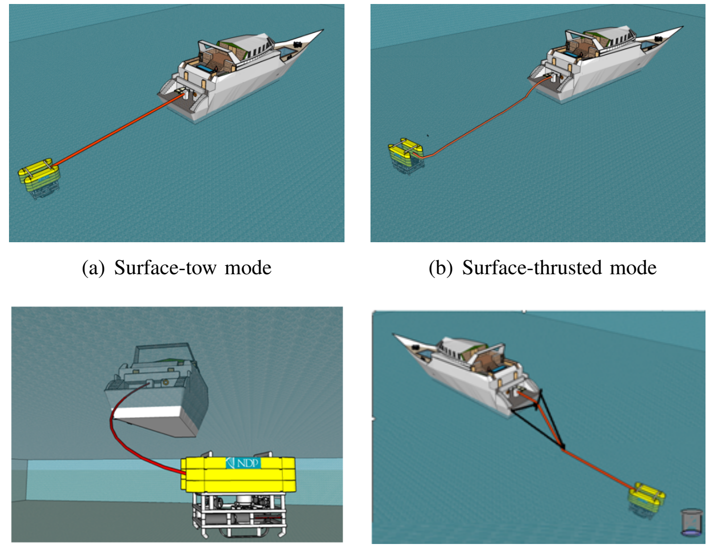
2) Operation Modes: ROV Latis is a vehicle with multiple modes of operation [6]. It can be operated on the surface as a survey platform either towed (Fig. 2(a)) or thrusted by 4 horizontal thrusters (Fig. 2(b)) to allow surge, sway and yaw. It can also operate as an ROV fully controllable in 6DoF by 4 horizontal and 4 vertical thrusters (Fig. 2(c)) or as ROV with submerged tow/holding line for operations in submerged tow or on station in strong currents (Fig. 2(d)). In these various modes of operation it is used in conjunction with a fibre optic umbilical and winch; the umbilical carrying vehicle power, control and data from sensors and instruments.

3) Technical Specifications: Technical specifications are given in Table I.

4) Advanced Pilot Interface: The Advanced Pilot Interface (Fig. 3) presents all important control data to the ROV pilot using familiar graphic controls & indicators. The pilot is able to use a combination of touch display, joystick, gamepad, mobile device, mouse or keyboard as input devices to generate commands, switch operating modes and enable/disable low-level controllers.

Set points can be entered numerically (e.g. using numeric control fields) or graphically (e.g. moving instrument pointers by mouse). The pilot can also easily switch between manual mode, semi-automatic modes (Follow Desired Speed & Course, Keep Current Position and Go To Position) and fully automatic mode (automatic navigation through way points).

5) 2D Topview Display: The 2D Topview Display (Fig. 4) shows a top view of the working zone and includes features like auto zoom, nav info display, floating heading indicators, visualisation of way points, real-time visualisation of sensors



(a) Surface-tow mode (b) Surface-thrusted mode

(c) ROV operation mode (d) ROV with submerged tow line in

Fig. 2. Operation Modes

Fig. 3. Advanced Pilot Interface

measurements (INS, DVL, USBL, GPS, etc.), distance & angle measurements tools, ROV-fixed, SHIP-fixed and free Lever Arms etc.

6) 3D Real-Time Augmented Reality Display: The 3D Real-Time Augmented Reality Display (Fig. 5) provides 3D real-time visualisation of the support vessel, ROV, ocean energy device, ocean surface, seabed, etc.

B. Reson SeaBat 7128 Sonar

In addition, as a payload sensor, Latis hosts a multibeam sonar, the Reson SeaBat 7128, which was for this experiment configured as a forward-looking sonar (FLS). This version of SeaBat 7128 operates at 400 kHz and illuminates a 128 ° horizontal sector. This system can be used either as a standalone or in conjunction with a permanently installed system for which it

TABLE I

LATIS ROV SPECIFICATIONS

Base Vehicle	
Chassis	Marine grade Aluminium
Payload	100 kg
Max. depth	1000 m
Thrusters	Seaeye SM4 (4H, 4V)
Power supply	11kW, upgradable
Instruments & Navigation Suite	
Multibeam sonar	Reson SeaBat 7125, 7128
Sidescan sonar	Tritech SeaKing sonar 325 kHz
Sound velocity probe	Reson SVP-24
INS	ixSea PHINS
Depth	CDL Microbath (Digiquartz)
DVL	RDI WorkHorse Navigator 600
USBL interface	iXsea GAPS, Kongsberg HiPAP
GPS (surface)	CSI-Wireless Seres or Submersible GPS GPRS-6015G
Obstacle avoidance	6 Tritech single-beam echosounders
Cameras	Bowtech Explorer-3K monochrome 2 LCC-600 monochrome Tritech Typhoon colour
Pan & tilt	Bowtech SS-109
Lights	3 Bowtech LED-1600 1 Bowtech LED-800 2 Tritech LED lite
Control System	
Embedded	Digital Logic EBX945 National Instruments Compact RIO
Topside	Control PC Tritech Typhoon colour
Max. depth	1000 m
Umbilical	
Length	400 m
Diametar	25 mm
Core	6 AC, 4 DC, 8 single mode fibres

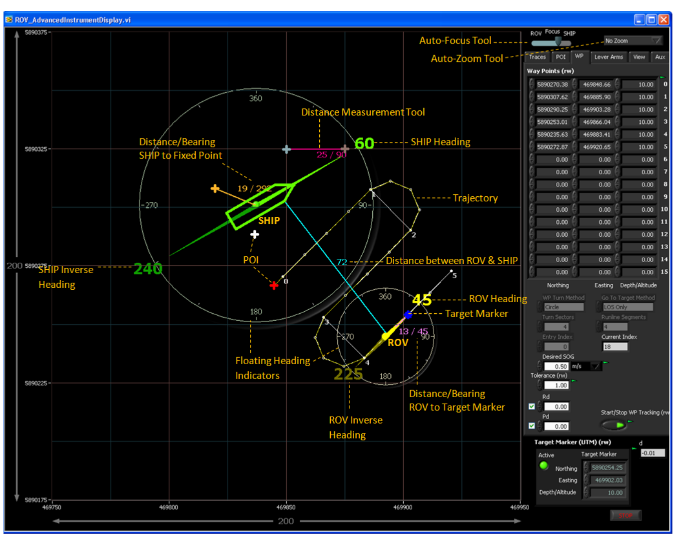


Fig. 4. 2D Topview Display

would provide intruder interception capability. When equipped with a narrow beam projector the SeaBat 7128 can perform a route surveys & all other activities listed for the SeaBat 7125.

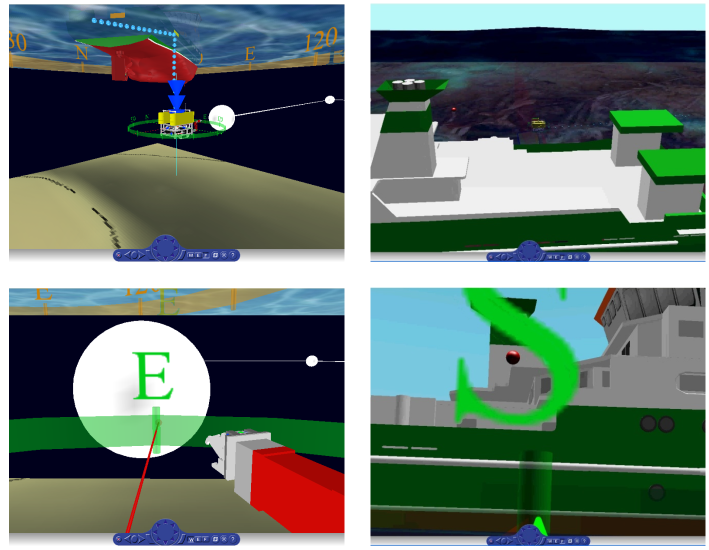


Fig. 5. 3D Real-Time Augmented Reality Displays

C. Goldrake UUV

The basis for Goldrake UUV, (Fig. 6), is a VideoRay Pro 4 ROV university kit acquired from VideoRay LLC, USA. Video Ray Pro 4 ROV equipped with two horizontal thrusters and one vertical thruster, and on-board compass and depth sensor utilized in navigation. After getting an idea for fast prototyping from the previous work [7] that integrated automarine module onto Video Ray ROV, CMRE added WLAN, GPS tracker, acoustic modem, and underwater aBox pressure vessel (for untethered operation) and University of Zagreb (UoZ) created control and navigation algorithms. CMRE and UoZ jointly created acoustic command interface between the ASV and the UUV that provided a software interface for DPAM (Florida Atlantic University) and Micro Modem (Woods Hole Oceanographic Institution - WHOI) acoustic modems. For this sea trial an acoustic modem from EvoLogics GmbH, Germany was integrated to have data to compare the performance of three different acoustic modems. This inexpensive platform (without expensive onboard navigation sensors, such as DVL or optical gyro-based IMU) receives the navigation updates that enable it to calculate its absolute 3D position (incorporating pressure sensor data). These updates are processed by the onboard navigation filter, and the UUV control system enables it to precisely follow a 3D line and arrive to the close proximity of the target.

III. LATIS-SCOOTER INTEGRATION

Latis navigation system was integrated with the mission management software used for the CMRE system of cooperative maritime vehicles [8], [9] (composed of two vehicles, the master ASV guiding the slave UUV to the target). In the proposed system, the ROV has to operate as the master vehicle in the cooperative vehicles missions. The software was modified to produce and send specific navigation commands to the Latis navigation software and to communicate with some

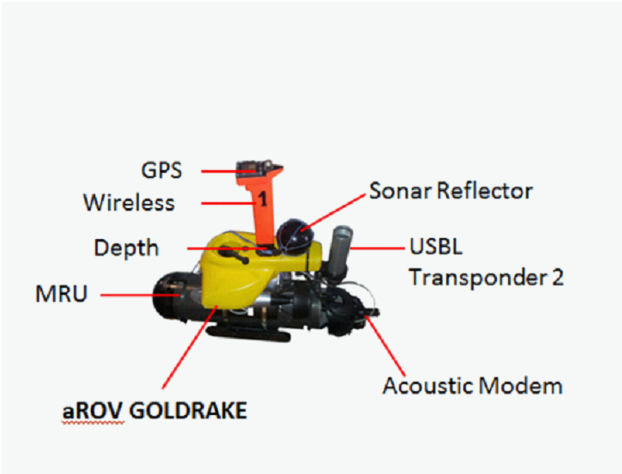


Fig. 6. Goldrake aROV

hardware modules (FLMS and an acoustic modem) positioned onboard the ROV. We added also the possibility to integrate and use onboard Latis different typologies of sonar and acoustic modems. Different devices have been tested during our at-sea trials to evaluate their performance in different scenarios (e.g. shallow and deep waters, acoustically noisy environments, etc.) to select the most suited to the mission requirements. Specifically, the devices that could be mounted on the ROV were:

- Forward looking multi-beam sonar: Reson SDK or Blueview P450.
- Acoustic modem: Evologics modem or WHOI Micro-Modem.

The mission management software is executed on a PC located on the support vessel (called Scooter-PC). A LAN connects the Scooter-PC to the Latis Navigation PC (also located on the support vessel and executing the ROV guidance algorithms in LabVIEW ©NI environment) and to the FLMS and the modem located on the ROV. Latis Navigation PC then communicates through the umbilical cable with the ROV onboard controller computers controlling the revolution speeds of the vehicle's 8 thrusters.

The architecture of the software running on Scooter-PC is based on MOOS-IvP [10]. MOOS-IvP is an open source C++ framework for providing autonomy to robotic platforms, in particular marine vehicles. MOOS-IvP is based on the mailbox paradigm: a community of processes subscribe to receive and publish variables from/to a database (MOOSDB). For the management and control of vehicles, the MOOS framework works according to the backseat-driver paradigm: a backseat computer executes the processes managing the mission and produces commands for a frontseat computer in charge of the vehicle low-level control [10].

In Fig. 7 a scheme of the main processes of our system is shown. *pScooter* is the process managing the ROV mission and producing the data/commands to the UUV. It reads the navigation data (latitude, longitude, depth, heading and pitch angles, etc.) coming from ROV Latis and the range/bearing of the UUV produced by the image processing module from sonar images. Then, *pScooter* estimates the position of the UUV and produces localization data and, on the basis of the current operative state, generates commands for the UUV and navigation commands for the Latis navigation software. The data directed to the UUV are then read and transmitted to the acoustic modem by dedicated processes (e.g. *pCommToUV*, *pNemoQueue*). To communicate with the Latis navigation algorithms, the process *pBridgeMOOS_Latis* is used. This process communicates with the Latis navigation software by using the LabVIEW shared variables mechanism. *pBridgeMOOS_Latis* makes available to *pScooter* all the variables regarding the status and pose of the ROV by publishing them to the MOOSDB. On the other side, it reads from the MOOSDB the produced navigation commands and makes them available to the LATIS navigation algorithms for their execution. Two possibile strategies were considered and implemented concerning the movement commands for the ROV produced by the mission management system:

- Latis control mode - *pScooter* computes the objective ROV 3D location along with the desired vehicle's pitch and heading. These data are sent to the Latis navigation algorithms that execute the received commands. In this strategy the holonomy of the ROV is fully exploited enabling the execution of movements with course angle differing from heading angle.
- Helm control mode - *pHelmIvP* process receives the desired Latis 3D position created by *pScooter* and produces the appropriate depth, heading and surge speed references. The commands produced by *pHelmIvP* are coherent with considering the ROV a non-holonomic vehicle like all the torpedo-shape AUVs generally are.

The two strategies have been tested in the trials. We used both to investigate the behavior and the performance of the system of cooperative vehicles in the two different cases: with the use of non-holonomic navigation for ROV we investigated the possibility to export the developed navigation concept also to torpedo-shape AUVs (e.g. REMUS AUV).

The two strategies can impact especially on ROV reacquisition behaviors design [11]. Reacquisition behaviors are specific movements of the master vehicle triggered when the UUV is "lost" by the tracking algorithm. This may happen either in case of the UUV exiting the sonar FOV, or in case of some errors/failures in the automatic image processing. Some purposely designed maneuvers of the master vehicle can in fact increase the odds the UUV is detected again. With the holonomic navigation, we can plan maneuvers in which a certain course is kept and the vehicle heading and pitch angles are modified to explore the search area with the sonar to redetect the UUV. Otherwise in the non-holonomic navigation typical of torpedo-shape vehicles, a change of heading implies a change of course angle and a change of pitch causes a change of depth: different typology of reacquisition maneuvers need to be planned.

The system is able to command acoustically the UUV to take a picture with its onboard camera. The image is then transmitted acoustically to the ROV and may be used to acquire more information about a possible target or an inspection location. Finally, *uScooter* and *pMarineViewer* processes provide the user a GUI to visualize the robots' movements, to configure the vehicles and to send direct commands to the UUV and to the ROV.

The MOOS-IvP framework eased the process of developing and integrating new software modules, and allowed us to easily test and tune the embarked code in simulated missions of the cooperative vehicles. This decreased the needed time to integrate and debug the different software modules and enabled us to easily substitute or add processes during sea trials.

IV. RESON SEABAT 7128 SONAR SOFTWARE

A. `reson_sdk`

The Reson SDK was developed to facilitate communication and data exchange between the `7kControlCentre` application for Reson sonar acquisition and CMRE image processing sonar. The SDK implements parts of the **SeaBat 7k Data Format v2.21**.

Handshaking and communication is implemented in the `FileClient`, for reading from Reson sonar *s7k* files, and in the `TCPClient` for TCP/IP communication with the acquisition software. For more details see the Reson software manual, [add citation here].

The `ResonSonar` class handles received messages and creates xy images from the phase/magnitude data. When data logging is enabled all received communication is logged in a binary file. These files can then be replayed by the `reson_sdk` library.

B. `iReson`

Support for the Reson sonar communication protocol was implemented in `reson_sdk`. The `iReson` application acts as the MOOS frontend for the Reson library. It was developed as the sister application of the `iBlueView` application, developed by A. Grati (CMRE). Modules providing `iBlueView` like capabilities:

- `PingGenerator` - retrieves the last sonar ping
- `MagImageBuilder` - builds the magnitude image
- `ImageColorMapper` - colormaps the magnitude image
- `JpegEncoder` - encodes the image for `BlueViewGUI`
- `MagImageToSharedMemory` - magnitude image and navigation data in shared memory for image processing applications
- `ROIExtractor` - extraction and XML packing of the desired ROI for `pBVImgProcessor`

were implemented to allow for easy exchange between the BlueView and Reson sonars. Additional modules were available in `iBlueView` but are now deprecated. Similarly, the `ROIExtractor` is to be deprecated in favor of shared memory image sharing. Modules interact on a generic **OpenCV** image container, `cv::Mat`. Figure IV-B shows the interaction of these modules with other LabUST and CMRE developed software.

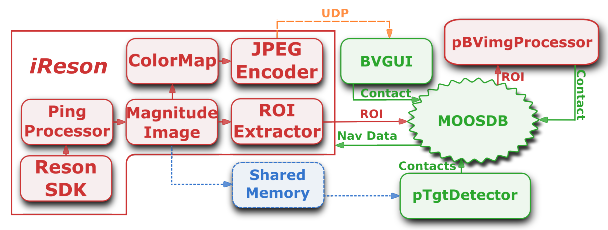


Fig. 8. iReson modules interaction

Currently the `iReson` software communicates with other CMRE software on three channels. Communication with the `BlueViewGUI` is done through UDP broadcasts. Compressed JPEG images are sent for display along with navigation data. Contact information can be generated manually or automatically. This is used to determine the region of interest (ROI) in the sonar image. Extracted ROI images alongside with navigation data are encoded in XML messages and published to MOOS. The ROI messages is used by the `pBVImageProcessing` application.

Transmission of images through MOOS has proven problematic. Multiple target detection would require multiple ROI messages exchanged between the `iReson` and other image processing application. To avoid this the shared memory channel was added for advanced image processing application. The advantage of shared memory are direct and fast access to the full image in full resolution. The disadvantage is that acquisition and processing applications have to run on the same system. However, this is negligible since both sonars are network based sensors and allow remote acquisition by default.

MOOS configuration is generated using the `plug` file. The subscribed and published variables are shown in table II. Variable names can be user specified, therefore we use generic names as specified in the `plug` file. Input variable names start with "`variable-name.in`" and output names start with "`variable-name.out`".

V. RESULTS

CMRE Program of Work for 2012 related to Autonomous Naval Mine Countermeasures Programme (ANMCM) included a two week sea-trial in Oct. 2012 in the project New Concepts for Autonomous Mine Neutralisation involving CRV LEONARDO, CMRE equipment and supporting technicians. This test explored the potential for this capability by introducing advanced autonomy concepts to unmanned vehicles, enabling them to perform their mission in the most efficient

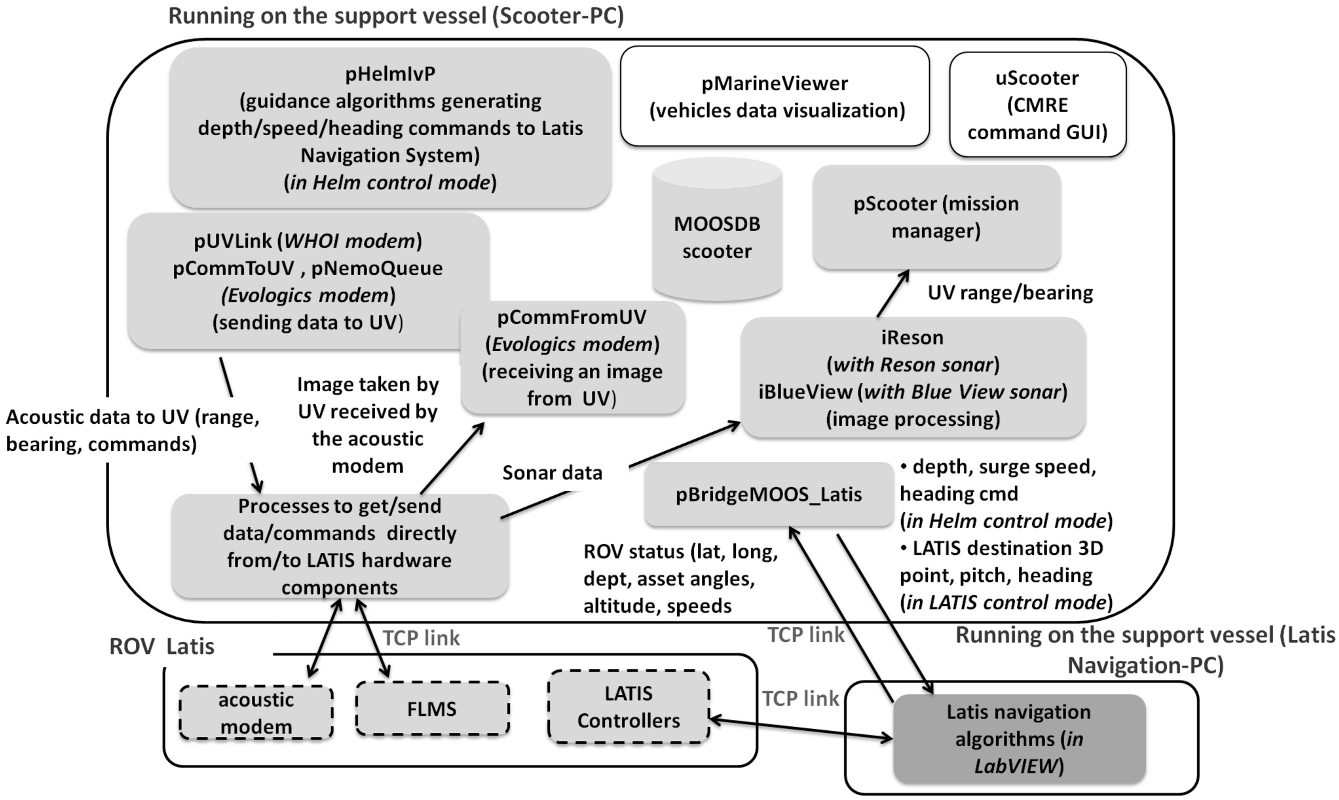


Fig. 7. Scheme of the system software architecture based on MOOS-IvP middleware(the different processes are shown - processes in white containers provide the GUI to the user). *Scooter* MOOS community manages the mission and produces commands to the UUV and to ROV Latis. The *pBridgeMOOS_LATIS* reads the variables produced by Latis and makes them available to MOOS processes. On the other side, it reads the navigation commands from the MOOSDB and makes them available to the Latis navigation algorithms on the Latis Navigation PC. The LabVIEW software running on this PC executes the received commands directly interacting with ROV controllers. The different computers are connected via LAN.

Subscribes	
Variable	**Usage**
`max-range`	maximum acquisition range
`min-range`	minimum acquisition range
`bool-image-auto-adjust`	enable/disable automatic contrast adjustment
`min-threshold`	minimum intensity threshold
`max-threshold`	maximum intensity threshold
`platfrom-latitude`	current latitude
`platform-longitude`	current longitude
`platform-heading`	current heading
`platform-pan-angle`	sonar pan angle
`platform-tilt-angle`	sonar tilt angle
`water-depth`	water depth below vehicle
`head-depth`	sonar depth below platform
`contact`	vehicle contact to determine ROI
`sonar-commands`	additional sonar commands
Publishes	
`xml-magnitude-image`	full image encoded in XML (deprecated)
`xml-jpeg-image`	full jpeg image in XML (deprecated)
`xml-roi`	published ROI in XML

TABLE II

IRESON SUBSCRIPTIONS AND PUBLICATIONS

and effective way, both operationally and financially. The objective was to test collaborative autonomous behaviours utilizing a smart Remotely Operated Vehicle (smart ROV) with its onboard forward looking sonar (FLS) and a small untethered "payload delivery" vehicle (UUV). Initial discussions that the suggested teaming can demonstrate delivery of a mine neutralisation vehicle to targets at significant depths and with stand-off distances longer than CMRE can demonstrate with its assets were proven to be true. The results of this sea trial should help convince the operational community of the effectiveness of the concept as the algorithms tested can be directly applied and this technology can quickly be transitioned to the modern minehunters equipped with Propelled Variable Depth Minehunting Sonar (PVDS).

Very stable Latis ROV platform enabled optimal image quality of the FLS. The sonar image processing and tracking algorithms, developed by UNIZG, enabled the localization of an inexpensive UUV in the sonar screen. CMRE's behavior-based software framework eased the process of developing and integrating new software modules needed for this experiment, and allowed us to easily test and tune the embarked code in simulated missions of the cooperative vehicles. This decreased the needed time to integrate and debug the different software modules and enabled us to easily substitute or add processes during sea trials. Latis ROV tracked the UUV via the sonar acoustically sending position fixes to it (Latis position, range and bearing to the UUV) and followed the UUV during its descent with a stand-off distance, as shown in (Fig. 10(a)).

A. Sonar Imagery and Control performance of dual underwater robot system

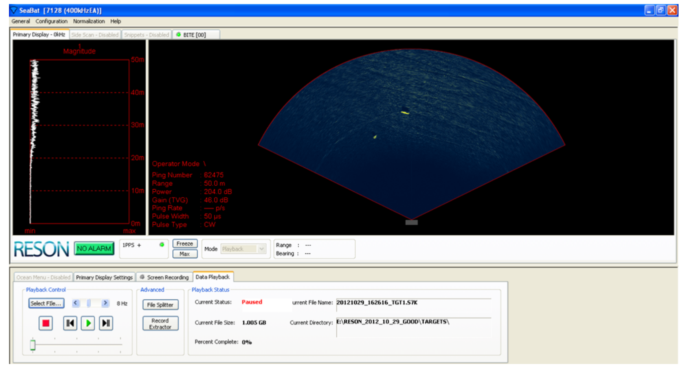
The concept of external system guidance being investigated was tested with Latis ROV re-acquiring a bottom target using a high-resolution forward-looking imaging sonar, and guiding the delivery vehicle to the target with minimal control information sent via simplified acoustic modem.

The control system of Latis ROV includes fast auto-tuning of low-level controllers, automatic thruster fault detection and accommodation, semi-automatic and fully-automatic control modes, optimal control allocation of thrusters, etc. The auto-tuning process of Heave (Depth) and Yaw low-level controllers involves the following steps: (1) Generate self-oscillations; (2) Wait for transient stage to finish; (3) Measure amplitude and period of steady-state oscillations; and (4) Find new values of controller gains using tuning rules. A novel set of tuning rules for underwater applications has been developed, which provides the optimal performance of low-level controllers in the case of configuration changes and the presence of disturbances (waves & sea currents).

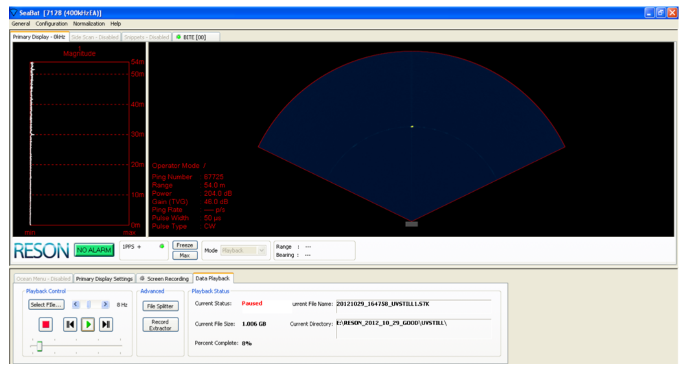
Once Latis ROV spots the target within the onboard multi-beam sonar image, the coordinates of the target in the Earth frame are recorded (using onboard altimeters and pressure sensors the depth of the target can be obtained). As shown in (Fig. 9(a)), the cylindrical type target needs to be distinguished from bottom clutter (a rock purposely placed for the sea trial next to it) and the Automatic Target Recognition algorithms, described in [12], can be used for this purpose. The coordinates of the target are sent to the UUV via an acoustic link.

Once the target location is known, multibeam sonar that is mounted on the Latis ROV acquires the UUV (might be long distance away from the target) highlight in the sonar image, (Fig. 9(b)). Since the multibeam sonar is a 2D sensor it will detect the slant range and bearing of the echo. The sonar processing algorithm with choose a 2D position estimate between clutter echoes and the UUV echo. To calculate the 3D position the UUV depth has to be know, however, due to the one sided communication the depth is unknown. Therefore, it is necessary to send the measured sonar slant-range and absolute bearing to the UUV. Via an acoustic link Latis ROV sends its x and y coordinates, slant-range, and the absolute bearing at a rate of 0.5 Hz, depending on the quality of the acoustic modem link. This is the minimum (40 bits) information that needs to be send to the UUV as its navigation update.

Combining the positional navigation update and depth measured onboard, the UUV can calculate its position in 3D. UUV draws a line between itself and the target. Then, the 3D line following problem can be observed as following two



(a) Cylindrical type target and a rock



(b) Goldrake on the way to 80m target

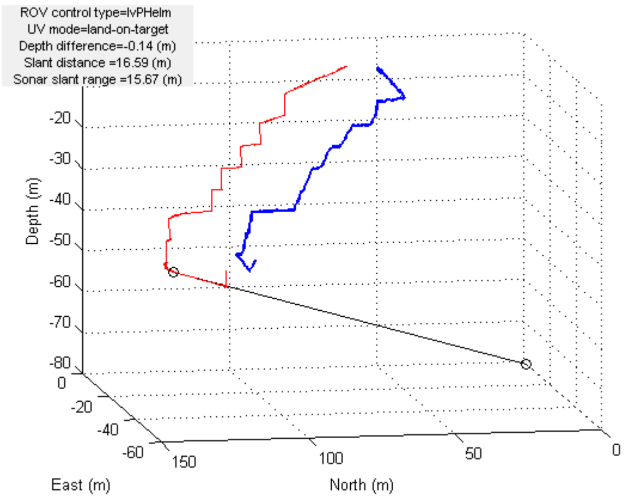
Fig. 9. Targets on 80 m depth and Goldrake in the water column

lines simultaneously: horizontal and vertical line. Models of the lines can be derived and the line-following controllers can be used to minimize the distance to the horizontal line (using the updates about the horizontal position arriving via accoustic modem) and to the vertical line (measuring depth with the pressure sensor). When the initialization procedure is completed (target location passed to the UUV), line following algorithm is engaged. The line following controllers implemented onboard of the UUV are explained in [5].

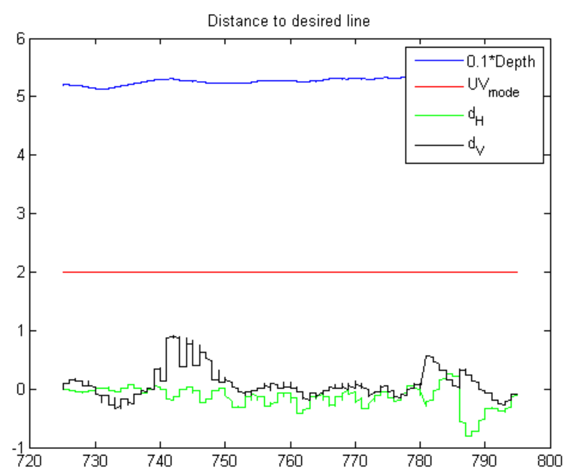
Latis and Goldrake 3D trajectories during one trial are showed in (Fig. 10(a)). A close look at Goldrake performance can been seen in (Fig. 10(b)).

Goldrake was acoustically commanded by Latis to descend at 52 m. During the descent Latis kept a stand-off distance (25 m) from the UUV. Latis maneuvered to keep the UUV into the sonar field-of-view. When Goldrake arrived at 52 m, the line-following command was issued. Then, the UUV started moving following a 3D line joining its current position to the target. During the movement, Latis followed the UUV tracking that with the sonar and acoustically sending position fix. The mission was successfully accomplished. Detailed data about the line following are showed in Fig. 10(b) where the vertical error d_V and horizontal error d_H with respect to the line to be followed (vertical and horizontal projections) are visible. The errors remain limited showing the Goldrake is following the desired line to the target.

The key features of this approach are:



(a) Latis (blue) and Goldrake (red) 3D position



(b) Goldrake performance

Fig. 10. Latis ROV and Goldrake joint mission to the target at 80 m depth

1) This approach utilizes one way communication between the Latis ROV and UUV (top to down). Any other approach would require UUV sending its depth to the Latis ROV.
2) The Kalman filtering onboard of the UUV enables the navigation in the cases when measurements are not available.
3) The multibeam sonar mounted on the Latis ROV need not have the target and the UUV in the field of view at all times, but only the UUV. If the target is in the field of view, corrected target position can optionally be sent to the UUV. This is useful in case of the positional drift of the ROV.
4) If the ROV drifts due to winds, waves, or currents, the UUV will not drift with it but it will stay on the line which has been determined initially.

B. Blueview P900 vs. Reson 7128 Sonar

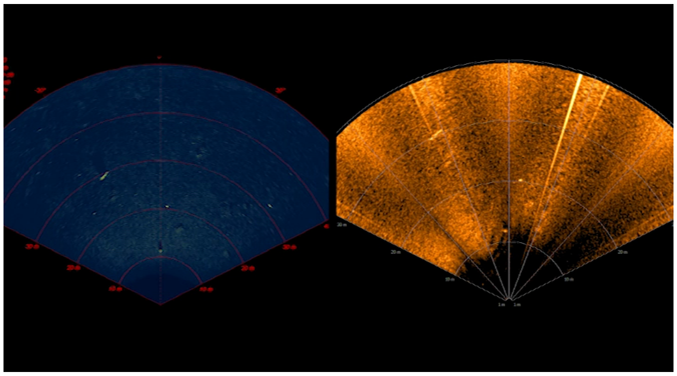
The high-resolution, multibeam imaging sonar available at CMRE and previously used for this project was the BlueView P900, operating at 900 kHz. Prior experimentation has shown that although other sonars might provide more detailed imagery, the BlueView P900 represents a good balance of size (important 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 35 m and be readily classified at ranges of nearly 20 m.

The trials described in this paper allowed us to compare the performance of the two forward looking sonars: Reson's SeaBat 7128 and Blueview's P900. Both of these can be considered as "guiding" sonars on an autonomous either surface or underwater vehicle in future. All subfigures in Fig. 11 contain three targets: 1) A rock at $\sim$ 10m from the sonar head, 2) Goldrake UUV, at $\sim$ 20-23 m from the sonar head, and 3) cylinder surrogate target, initially at $\sim$ 30 m from the sonar head (to the left). The (Fig. 11(a)), (Fig. 11(b)), and (Fig. 11(c)) show the images of the movement of the UUV which reaches the cylinder target in (Fig. 11(c)). From all the figures in (Fig. 11) it can be seen that the resolution of 7128 sonar is better than that of P900. The higher resolution would contribute to the performance of the Automatic Target Recognition algorithms, described in [12], as it is clear from the imagery that there exist a distinct shadow of the cylindrical target in case of Reson sonar and this is not always the case for Blueview sonar. Moreover, our automatic target tracking algorithm never lost the track of Goldrake UUV when Reson sonar was used which sometimes occurs when Blueview sonar is used for tracking and guiding.

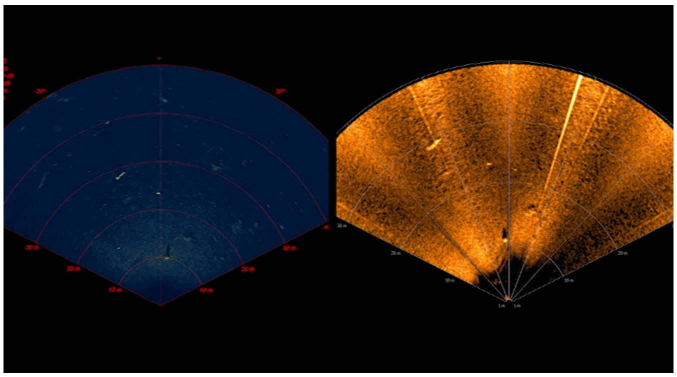
Additional objectives of the trial, not discussed in this paper, were to send the image of the target via accoustic communication link from the UUV and to perform the guiding over longer distances (beyond the range of the above mentioned sonars) via the ship based ultra short baseline (USBL) acoustic positioning system. The first investigates the potential use of the camera (which comes as a standard sensor on the commercial ROV being used for testing) for providing optical identification information on the mine target as the UUV lands, while the second investigates the potential of guiding multiple underwater robots by a capable robot over extended distances.

VI. Conclusion

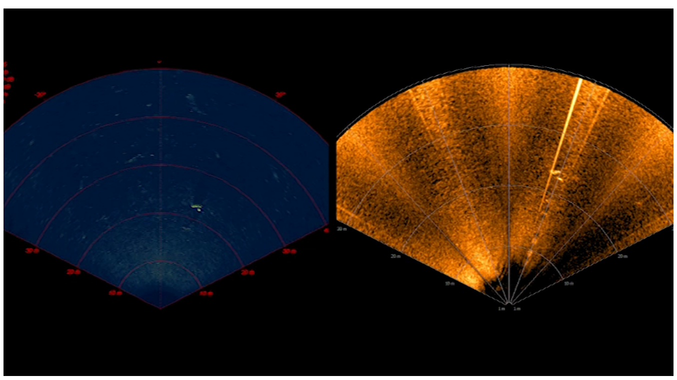
The use of autonomous systems has the potential to transform existing MCM capabilities in NATO from a Cold War legacy focused on time consuming clearance with surface ships, to a quickly deployable (air/sea lift), scalable system which offers an order of magnitude increase in speed of operation, reduction in life-cycle cost and increased interoperability over existing systems. The use of autonomous systems for MCM also reduces risk to personnel and expensive materiel, i.e., one goal is to "get the man out of the minefield." This transformation is under way today as seabed surveys for mine detection are now routinely conducted with autonomous



(a) Three targets at: 10m, 20 m (both center), and 30 m (left)



(b) Goldrake (middle of the screen) moving toward the cylinder



(c) Goldrake finishing its mission, reaching the cylinder

Fig. 11. Reson 7128 versus Blueview P900

underwater vehicles (AUVs), resulting in an exponential increase in search speed capability. The introduction of one shot weaponised AUV type vehicles has also hugely reduced the traditionally time consuming neutralisation part of the MCM process. However, neutralisation efforts are still operator intensive, and require the vehicles to be tethered to a command ship for control purposes.

In the sea trial the smart ROV Latis from the University of Limerick (UL) was used as a guiding platform and an automated Video Ray Pro 4 ROV was used as an inexpensive UUV - could be considered as one shot weaponised AUV type vehicle. This method enables precise navigation of multiple inexpensive UUVs in a coordinated fashion in 3D space, without costly on-board 3D, 6 DOF pose estimation sensors (eg., optical gyro-based IMUs), velocity estimation Doppler velocity logs (DVL), or deployed underwater acoustic positioning systems (Long baseline – LBL or Ultra Short Baseline - USBL). The 3D navigation accuracy of 20 cm in the horizontal and 10 cm in the vertical plane was achieved for the path length of hundreds of meters. This accuracy assures the precise underwater navigation required by most of the applications of the underwater robots. The collaboration with the Mobile & Marine Robotics Research Centre at University of Limerick raised our project's output to the next level since we, not only demonstrated the external guiding concept in 3D, but also in environmental conditions equivalent to the conditions of current mine disposal operations.

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