Cooperative Deep Water Seafloor Mapping with Heterogeneous Robotic Platforms

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Abstract—**This paper describes the PISCES system, an integrated approach for fully autonomous mapping of large areas of the ocean in deep waters. A deep water AUV will use an acoustic navigation system to compute is position with bounded error. The range limitation will be overcome by a moving baseline scheme, with the acoustic sources installed in robotic surface vessels with previously combined trajectories. In order to save power, all systems will have synchronized clocks and implement the One Way Travel Time scheme. The mapping system will be a combination of an off-the-shelf MBES with a new long range bathymetry system, with a source on a moving surface vessel and the receivers on board the AUV. The system is being prepared to participate in round one of the XPRIZE challenge.**

I. INTRODUCTION

Underwater robotic vehicles have already proved to be extremely valuable in most scenarios of underwater surveying, particularly in what concerns deep water environments. Autonomous Underwater Vehicles (AUVs) operate with no physical link with the surface or any other structure, and, therefore, are a preferred tool for long range ocean exploration. However, their endurance and range are still somehow limited and operations in deep waters still require the use of dedicated (and expensive) support vessels. During the last decade, INESC TEC has been involved in the development of several research lines to increase the general concept of *autonomy*. These have been incorporated in autonomous vehicles, achieving longer missions, in deeper waters, with less intervention from operators.

The "Shell Ocean Discovery XPRIZE" was recently launched as an extreme challenge, with the main objective to foster the development of innovative/disruptive solutions for detailed autonomous mapping of large areas of the ocean floor[1]. This vision is aligned with the long term goals of INESC TEC and the challenge was an excellent opportunity to promote some of concepts that have been planned. Therefore, INESC TEC has registered for the challenge and the proposed solution that has already been selected to the first round of trials, planned for the fall of 2017 – the PISCES system. This is a joint effort to provide a fully autonomous system for survey of large areas of the ocean, in deep waters, and required many new developments that will be discussed in the paper.

The paper is organized as follows. Section II summarizes the main requirements for Shell Ocean Discovery XPRIZE, which we have considered as our own requirements for the next stage of system development. Section III provides an overview of the state of the art in terms of large scale surveys performed with autonomous platforms. Section IV describes the PISCES concept of operation, and details system components, both in terms of vehicles, and also in terms of subsystems that will be used to solve the main challenges. Çastly, in Section VI, we present the concluding remarks.

II. MAIN CHALLENGES/REQUIREMENTS

For round one of the competition, the Shell Ocean Discovery XPRIZE requires mapping a minimum area of 100km^2, with a 5m horizontal resolution, and a 0.5m vertical resolution. This has to be done in 2000 meters of water depth, within a time limit of 16 hours. Furthermore, the full system has to departure and return to the coast, and operate up to 50 miles offshore, without any physical intervention. For the final round, planned for late 2018, these requirements will become even more challenging, namely with an increase in mapped area and depth to 4000 meters.

In separate, some of these requirements can be achieved with the state of the art solutions, so the overall challenge is to advance the missing technological solutions, and to accomplish all the features at the same time.

Most AUV assignments are defined in term of geographic coordinates. To accomplish them, an AUV requires a navigation system that provides a real time estimate of the vehicle position. This serves for the control system to make necessary corrections in trajectory, and, at the same time, it allows sensor data to be spatially tagged. At the surface, GNSS (Global Navigation Satellite Systems, such as GPS) signals are usually sufficient to provide a position estimate, and, if necessary, accuracy can be improved with differential corrections (DGPS) or even with inertial sensors. Below the water surface, GPS signals are not available, so other solutions must be employed to allow the computation of vehicle position. Pressure

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[1] for more information, see http://oceandiscovery.xprize.org/

sensors, digital compasses, inertial units with accelerometers and gyroscopes, and Doppler Velocity Loggers (DVL), are typical sensors readily available for integration. All these data can be fused together using an extended Kalman Filter, or another data fusion algorithm. However, even with data from multiple sensors, the position estimate exhibits an error that grows in time due to continuous integration of biases, so it requires an external aid to provide an absolute measure and avoid divergence. For relatively small operation areas, this is usually ensured with the assistance of acoustic transponders, deployed in the area, and the exchange of acoustic signals to estimate position, based on measurements of time of flight and multilateration techniques. The practical ranges of these systems, however, is limited to only a few kilometers, and the need to deploy acoustic beacons in the operation area, prevents the use of such systems in remote, unstructured environments.

III. RELATED WORK

Seafloor mapping can be done with multiple types of sonar systems, either directly from a support ship, or installed in robotic platforms. These can be operated remotely, or programmed to follow specific motion patterns to ensure maximum coverage and accurate maps. In terms of robotic platforms, INESC TEC has significant experience in the development of autonomous underwater vehicles, autonomous surface vehicles, and complementary systems with heterogeneous vehicles. Our PISCES approach builds on these earlier developments to extend mapping operations to very large areas of the ocean floor. The relevant references will be provided with the details of the proposed solution.

Multi beam echo sounder (MBE), synthetic aperture sonar (SAS) and side scan sonar (SSS) can be used to collect the acoustic backscatter data obtained from reflection of acoustic energy back towards a sonar device where its intensity and travel time can be measured. Travel time can be converted into distance and that allows for drawing bathymetric maps of the sea floor. In backscatter systems, the acoustic source is in the same location as the receiver or array of receivers, while in forward scatter systems the acoustic source and the receivers are at different positions. Forward scattering systems can also be used to measure the travel time regarding that the source is synchronized with the receiver [1]. Conventional SSS and MBE can be used to detect anomalies in the seafloor, however SSS is more dedicated for images and MBE for bathymetry. In fact, SSS do not measure water depth but the images contain indirect bathymetric information in form of a backscatter increase or decrease depending on the seafloor slopes. MBE receive the seafloor backscatter on a series of narrow beams (in the across-track direction) and thus allow for the determination of depth across the swath (at the resolution of the receive beam spacing) and the recording of the backscatter time series at known angles across the swath [2]. Because the beam footprints are larger towards the edge of the swath, the bathymetry resolution decreases with the MBE altitude from the seafloor (e.g. for the MBE Reson 7125 a resolution < 1m is achieved when operated at 50m altitude). When SSS and MBE are operated simultaneously from the same platform the SSS backscattering images and the MBE bathymetry can be greatly improved by merging the information from both systems [3], providing the SSS images with depth information and MBE bathymetry with higher resolution. More recently synthetic aperture sonar (SAS) together with interferometry techniques are emerging as an imaging technology that can provide centimeter resolution over hundreds-of-meters swath and detailed bathymetry of the seafloor [4]. SAS combine several acoustic pings to form an image with much higher resolution than conventional sonars. It is also possible to merge SAS and MBE data-sets to create a full-swath high-resolution bathymetric map. The SAS combination of sensors allows very-high mapping rates at very-high bathymetric resolution. Building redundancy into the survey pattern allows the SAS to be used to calibrate the MBE and vice-versa [4]. The SAS based systems easily presented resolutions lower that 50x50 cm, however they have to transmit pings at a high rate since the platform/AUV cannot travel further than half the length of the receive array per ping interval. The rather frequent ping transmissions also require significant energy, which can limit the mission duration.

IV. THE PISCES SYSTEM

The main innovative idea behind the PISCES system is the cooperative use of complementary marine robotic platforms to yield an efficient and effective solution for deep water exploration. These platforms will be jointly operated and will incorporate a distributed acoustic navigation and mapping system. The main components of the PISCES system are four heterogeneous autonomous vehicles:

- A deep water AUV – a 5000 meter rated underwater vehicle, with payload sensors for image and sonar mapping, and also an array of acoustic receivers for long range, large swath mapping.
- The Roaz ASV – a long range Autonomous Surface Vehicle for AUV launch and recovery, also working as an acoustic source for long range bathymetry.
- Zarco and Gama ASVs – two smaller vehicles used as moving acoustic beacons, ensuring a constant (bounded) accuracy of the AUV navigation system.

This system will collectively address the main challenges of long term operations in deep waters. In terms of navigation, our solution is to install acoustic navigation transponders in moving vessels – the two small ASVs – and this way extending the operational range of the acoustic network, therefore ensuring a bound in the error of the AUV position estimate. Nonetheless, the conversion of time of flight into distances requires an accurate knowledge of the sound velocity, that may vary significantly within the water column. For this reason, it is also important that the AUV carries a CTD sensor to measure the sound velocity profile as it dives to the operational depth.

Energy management is always a fundamental aspect of the operation of autonomous vehicles, and it is even more relevant in the case of the PISCES system, as it is planned to extend both the limits of velocity and range for man portable vehicles. One of the ways to save power on the AUV side, and to improve the navigation accuracy at the same time, is to implement a ranging technique known as One Way Travel Time (or OWTT). With a synchronized clock between transmitter(s) and receiver, and a known transmission sequence, the AUV can estimate its own position just by listening to the signals arriving from the transmitters. The absence of transmissions from the AUV side results in the power savings, and, at the same time, free the acoustic channel to allow a higher transmission rate from the acoustic beacons.

Another limitation of current technology is related to the performance of existing sonars, mainly in terms of range, resolution, and swath. To achieve the resolution required by the Shell Ocean Discovery XPRIZE using a commercial sonar, the AUV would have to navigate relatively close to the bottom, requiring very close transects to ensure full coverage of the survey area. This would force the AUV to travel at extraordinary speeds to complete the survey within the time limits and, even if possible, would require a tremendous amount of energy and cause a blurring in the data obtained. To overcome these limitations in terms of sonar characteristics, a new approach for sea bottom mapping will be adopted, comprising of a distributed system, with one component at the surface (on an ASV) and an array of receivers on the deep water AUV.

A. The DART AUV

The DART AUV (for *Deep water Autonomous Robotic Traveler*) is a customized deep water version of the MARES AUV, a portable hovering vehicle in operation for more than 10 years. The MARES AUV was developed with a modular approach, with a single pressure housing holding all batteries and electronics [5]. In the deep-water version, this housing was replaced by a glass cylinder to withstand 5000 meters of water depth. All external subsystems are installed in flooded sections, and therefore can be reused from the original vehicle, with the proper selection of pressure rating versions of the sensors and actuators. The overall vehicle has little over 50kg, with a length of 2.4m and a constant diameter of 20cm [6]. The thruster configuration, with two independent horizontal thrusters and two independent vertical thrusters, allows the AUV to hover in the water column, a useful feature for close-range video surveys of the seafloor. To facilitate the descent in the water column, while saving energy, the vehicle will have a drop weight in the nose, that will be released once it approaches the desired depth.

The energy is provided by rechargeable Li-Ion batteries, with a current total of 800Wh of energy. The navigation package includes a pressure sensor, hydrophones for acoustic navigation, an inertial unit with compass and inclinometers, and a digital echo sounder to measure distance to the bottom.

Currently, all mechanical components and onboard electronic subsystems have been implemented for the first tests at the water tanks of INESC TEC (figure 1).

In terms of payload, the XPRIZE version of DART will have:

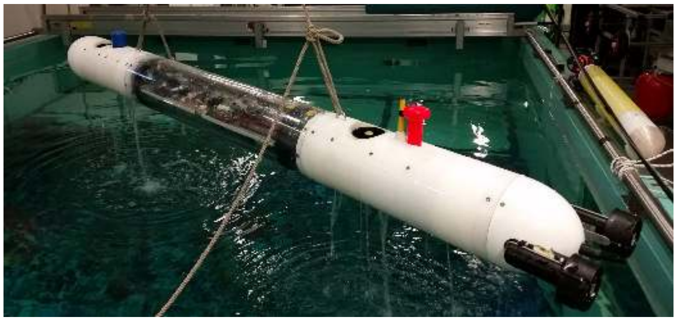

Fig. 1. DART AUV in the test tank.

- A down-looking underwater digital camera (and lights) to capture digital pictures and videos of the sea bottom and other features. This camera is COTS IP camera from Mako, installed inside an aluminum pressure proof housing;
- A multibeam echo sounder, providing a direct reading of multiple distances to the sea floor. The multibeam echo sounder currently available is a Delta T from Imagenex. Although the range (altitude) is quite limited (100 meters), the main purpose of the echo sounder is to provide the calibration for the surface-based long range bathymetry sensor. If necessary to increase swath, this multibeam echo sounder may be replaced by another with a larger range;
- An array of acoustic recorders located along the outside of the hull, as part of the distributed long range bathymetry system. These acoustic recorders will receive and register all the echoes of the sound transmitted from the surface and reflected in the sea bottom.
- An onboard CTD to determine several characteristics of the water column: the water density will allow an accurate conversion from pressure to depth, while the sound velocity profile will improve the accuracy of range measurements based on time of flight of acoustic signals.

B. The Roaz ASV

Roaz is an electric powered 4.2m long catamaran equipped with a precision dual band RTK GPS receiver and inertial navigation system, providing not only precise location for navigation purposes but also accurate geo-referencing of sensory data [7].

Above water, Roaz can be configured with a selection of equipment already proven in the field, such as a thermographic and a visible spectrum cameras (with on board processing that can be applied in search operations) and a RADAR used for large obstacle detection. In addition, for close range environment 3D modeling and obstacle detection the system can be equipped with a 3D Velodyne LIDAR. This robotic vehicle is also typically equipped with a single beam echo sounder, an Imagenex DeltaT multibeam sonar and an Imagenex Sportscan side scan sonar. These sonars are used for underwater environment modeling and bathymetry tasks.

Fig. 2. Roaz carrying the MARES AUV during "euRathlon 2015", in Italy.

Fig. 3. Sequence of pictures during the deployment of the MARES AUV from Roaz ASV.

For above water communications when the vehicle is within range, Roaz is equipped with an IEEE 802.11a link, an Iridium satellite communications link and a long range Freewave serial radio link. The on-board computer is responsible for the autonomous mission control, and can be used to process the vehicle sensors to detect relevant events or perform sensor oriented missions.

Roaz has already been used to carry and deploy the MARES AUV, during the “euRathlon 2015” robotics competition in search and rescue scenarios [8]. Figure 2 shows Roaz with the MARES AUV on board, during the transportation phase, while figure 3 shows the deployment sequence, with Roaz navigating. In the PISCES system, Roaz will have a dual purpose: as a transportation, launch and recovery system for the deep water AUV, and as a host for the acoustic emitter for long range bathymetry.

The onboard energy storage system is being increased in PISCES to comply with the requirement of transiting 50 nautical miles between the coast and the operation area, to track the AUV motion during the survey, and to return to the mission control station. The PISCES configuration will complement the batteries with an electric generator, to achieve a maximum range of 300km.

Since the DART AUV is significantly longer and heavier than the MARES AUV, the launch and recovery system will be installed along the center of the vessel, which will require a reconfiguration of the onboard subsystems, as can be seen in figure 4.

C. Zarco and Gama ASVs

Zarco and Gama are smaller catamaran ASVs that also use a fusion of inertial and GPS data to navigate [9]. They can be programmed to follow specific trajectories or to hold position, autonomously, or they can be teleoperated. Zarco and Gama have been in operation since 2006, either independently (for bathymetry, for example) or coordinated, providing moving baselines for AUV navigation [10]. They have already been used as coordinated platforms for acoustic trials as described in [11].

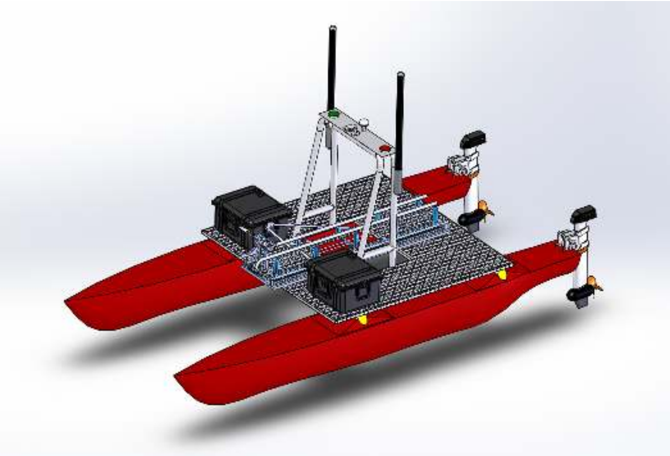

Fig. 4. Schematic of the reconfiguration of Roaz with the AUV launch and recovery system along the center.

Fig. 5. Zarco ASV with 2.7m long pontoons.

In the PISCES system, the lateral flotation pontoons were extended to provide extra flotation (fig. 5), and to incorporate the new energy storage system and the new propulsion systems to increase both maximum range and velocity. During a survey, they provide synchronized acoustic pings for the navigation of the AUV.

D. Specific Subsystems

For the development and deployment of the full PISCES system as envisaged, it was necessary to design specific solutions for certain vital subsystems.

1) Long Range Bathymetry: The proposed system aims at take advantage of merging the information of MBE and SAS systems, taking in consideration operational limitations to accomplish the mission. In order to perform a long endurance mission: (i) the AUV has to travel at a high altitude (200m) for reducing the number of transepts needed, which will reduce the MBE resolution for unacceptable values when in standalone operation, such problem aims at being solved merging the MBE with SAS data sets; (ii) the power needed for SAS ping transmissions limits the mission duration, such problem aims at being solved using the navigation pinged available at the surface vessel as acoustic source for the SAS and solving the transmission/reception synchronization problem with the time instant at which the navigation ping is received at the AUV.

The approach for sea bottom mapping is based on a complementary system: (i) a high directional and powerful sound source at the surface vehicle and a 2D array of receivers at the AUV; (ii) a multi-beam collocated at the AUV. System (i) transmits high power pulses that are received at the AUV when traveling downward, and are used for navigation an also for synchronization of the echoes received after sea bottom reflection. The 2D array allows for the implementation of a synthetic sonar approach for separating the echoes from 2D different directions. The (low resolution) bathymetric information provided by system (ii) is used to calibrate system (i) since it is expected that the information of system (i) is contaminated with acoustic channel distortion. In order to maintain the channel distortion at an acceptable level, the surface vehicle will be maintained in the vertical above the AUV.

In terms of frequency range, the acoustic signals for long range bathymetry will use frequencies between 40 and 70KHz, a balance between high frequencies that convey more information, and low frequencies that have less attenuation with distance. The pressure levels will be quite strong, above 220 dB re 1μPa@1m, but naturally conforming to the safety limits for cetaceans at sea.

2) Vehicle Navigation: The navigation system is a crucial piece of any ocean exploration mission. The PISCES approach incorporates both ubiquitous and innovative systems and techniques, building upon many years of experience and expertise in the integration and development of similar solutions. All ASVs will rely on Global Navigation Satellite System (GNSS) receivers as the primary source of navigation data. Current up-to-date receivers are already capable of delivering submeter accuracy in Single Point Positioning mode. This is the case when resorting to Satellite-Based Augmentation Systems (SBAS), like the EGNOS constellation, covering Europe, or the WAAS constellation, covering the United States of America. At the same time, an appropriate multisensory-fusion strategy will be employed, so that an improved real-time position accuracy of the ASVs can be obtained. Such strategy combines sensor measurements from the GNSS receiver, position and velocity, together with the inertial measurements, specific force, angular rate, and magnetic field, provided by the Inertial Measurement Units (IMUs) that equip all the ASVs. The use of precise GNSS receivers allows to obtain at post-processing time decimeter-level position accuracy. This can be obtained by post-processing the GNSS data using any of Precise Point Positioning (PPP) processing services, available online. This will be of utmost importance for delivering a precise mapping of the area under analysis.

As the ASVs are intended to serve as acoustic beacons for AUV localization, it is important for the AUV to know the positions of the beacons to estimate its own position in the earth-fixed referential frame. A trivial option would be to transmit the ASVs' positions over time at a reasonable frequency but it would come at the cost of communication devices, which could only achieve low data rates with considerable delays for the considered depth. A more suitable option is to use the ASVs ability to track position references, whose positions over time can be transmitted to the AUV beforehand to enable precise localization. Those references shall explicitly consider the ASVs constraints, namely maximum speed, currents and wind impacts. This mechanism of commanding the ASVs to track position references has been demonstrated even with the presence of currents, as described in [12].

All ASVs will form a constellation of acoustic beacons for the deep-water vehicle. To save power at the AUV side, these vehicles will be programmed to send specific coded pings at predetermined patterns synchronous with the PPS (Pulse Per Second) signal from GNSS receivers. The AUV will know this pinging pattern and the trajectories of the beacon ASVs and, therefore, will be able to estimate distance to each ASV and its global positions through triangulation. Throughout the mission, the time and amplitude of the tide will also be logged, to allow for further corrections of depth data.

Data post processing will contribute to improve the accuracy of the seafloor mapping and its geo—referencing. Such post processing will take place upon mission completion and it will be performed at several levels. While real time GNSS based positioning of surface vehicles will be accurate enough for guidance and control purposes, raw data from GNSS receivers and from IMUs will be recorded along the mission for post processing. Such data will then be fed to a smoothing algorithm in order to produce high accuracy position and attitude information of the navigation beacons carried by the surface vehicles. The AUV and the ASVs will also store all raw acoustic positioning data during the operation, which will be post processed at the end of the mission. The post processing algorithm will rely on a stochastic smoothing filter that will use all the recorded data to estimate the position and attitude of the AUV at each moment of the operation. Such procedure will reduce the uncertainty associated with the estimation of the AUV pose. At another level, processed payload data (acoustic echoes captured by the AUV carried receivers) will also be fused together with positioning/attitude data to further reduce the overall mapping error.

During the mission, the Roaz ASV will mimic at the surface the same trajectory planned for the AUV. This will ensure that it will be in the vertical of the AUV, maintaining a preferred

Fig. 6. Schematic overview of the LARS for the DART AUV, in a retracted position. The LARS is actuated to extend and rotate the cradle so that the AUV slides into the water tail-first.

path for sound propagation and reducing errors introduced by ray bending of acoustic waves.

3) Remote Launch and Recovery System: In our approach, the deep water AUV is transported to the operation area onboard the Roaz ASV. For the deployment of the AUV, and later recovery from the surface, a special launch and recovery system (LARS) has been designed. This had to be fully instrumented, to allow remote supervision of the launch and recovery procedures. The system is controlled by a dedicated control box placed in the Roaz ASV.

The LARS system is composed of a moving aluminum and stainless steel structure activated by 12V linear actuators. In a retracted position the LARS seats completely inside the envelope of the ASV frame (fig. 6). When activated, the AUV cradle will travel 700mm outside the frame and will then tilt to an angle of approximately 40 degrees. In this position a considerable portion of the cradle will be underwater, ensuring that the AUV enters the water while still performing a controlled slide, instead of simply being dropped in the surface. The restrain system is then disabled freeing the AUV to slide along the cradle. By this time the AUV is only secured by a claw assembly connected to a winch. The winch is then disengaged to deploy the vehicle in a controlled manner, and when the AUV is fully in the water the claw system is triggered to completely release it.

V. OPERATIONS PLAN

A. Logistics

All components of the PISCES system will be shipped in a single ISO Intermodal shipping container of 2.44m wide by 2.59m high, and 12.19m long, as required by the competition rules. The components will be disassembled in large sub components to facilitate packaging. At the Shore-based facilities, these large modules will be rapidly assembled together to form the 4 Entry Components of the PISCES system: one deep water AUV and three ASVs. The deep water AUV will be carried to the Competition Area by the Roaz ASV, and it will be attached to the transportation berth at the shore-based facilities. All these components will undergo a sequence of pre-mission tests before deployment, together with the supervisory infrastructure, based on standard computers and communication systems. All ASVs will need a small winch for deployment. The maximum weight to be lifted is Roaz with the AUV, which will be less than 500kg. When in water, a final set of tests is required to assess the correct operation of all the propulsion systems, and the corresponding telemetry systems. All Entry Components will work using on-board electrical energy, based on rechargeable batteries (Lead-Acid and/or Lithium Ion) and, in the case of the ASVs, will have a backup gas-powered electrical generator. Upon the successful completion of all the preliminary tests, the overall system will be deployed from shore and will move to the Competition Area with no further physical intervention from the team. The operations plan will then be a sequence of major phases, as illustrated in figures 7, 8, 9, and 10.

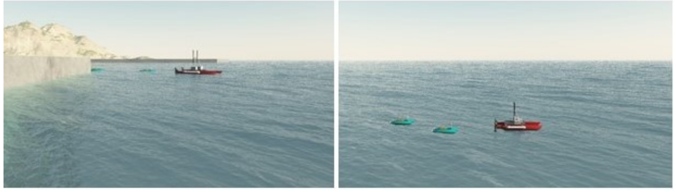

Fig. 7. Phase 1: ASVs depart from the shore-based facilities and move to the competition area. Roaz ASV leads the group, carrying the AUV, and will detect other vessels in the vicinity using radar, optical, and thermal imaging.

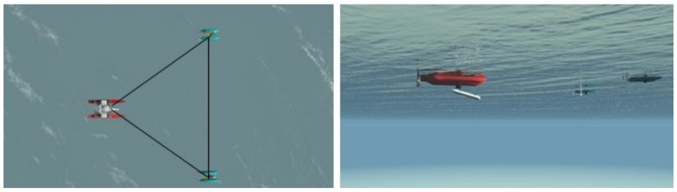

Fig. 8. Phase 2: Upon reaching the competition area, the navigation support ASVs move to position. Roaz launches the deep water AUV that dives to the operational depth and the survey begins.

B. Mission Plan

All four robotic vessels will have a specific mission file to complete. The AUV will start diving nose-down to the right height above the sea bottom, when it releases the drop weight and assumes an horizontal pose. It will then start a lawnmower pattern, with 10legs of 10km, separated by 1km, with a constant height above the seabottom. To conclude the full mission within the time limit of 16 hours, the AUV and all ASVs will travel at 2m/s.

During the mission, and particularly during transit to the Competition Area, special attention will be given to marine traffic in the area, not only using information from the onboard sensors of the ASVs, but also from available broadcasts. The position of the ASVs will also be announced using AIS transmitters.

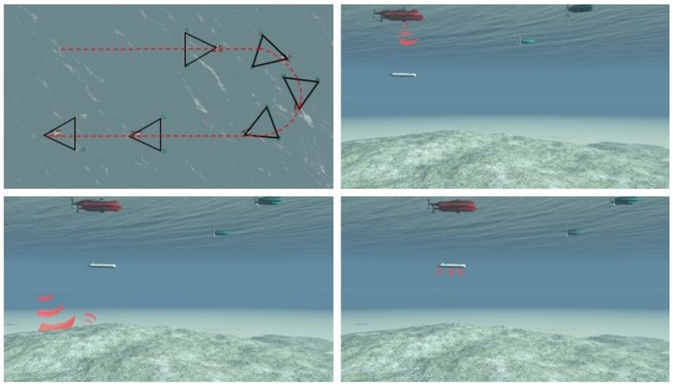

Fig. 9. Phase 3: During survey, Roaz trajectory mimics AUV motion at the surface, ensuring a vertical alignment. Zarco and Gama form a triangle with Roaz, providing a moving acoustic baseline for AUV localization. At the same time, Roaz acoustic system transmits acoustic pulses for long range bathymetry of the sea bottom.

Fig. 10. Phase 4: At the end of the survey, the AUV surfaces and is recovered by Roaz. All vehicles return to the shore-based facilities for recovery.

VI. CONCLUSION AND FUTURE WORK

Autonomous Underwater Vehicles are preferred tools for long range ocean exploration, but their endurance and range are still somehow limited and operations in deep waters still require the use of dedicated support vessels. This paper describes the PISCES system, an integrated approach for fully autonomous mapping of large areas of the ocean in deep waters. Although this system incorporates many concepts that were already under development at INESC TEC, it was encouraged by the recently launched "Shell Ocean Discovery XPRIZE" challenge.

A deep water AUV will use an acoustic navigation system to compute its position with bounded error, which is typically limited to a few kilometers of range between acoustic beacons and vehicles. In the PISCES system, the acoustic sources will be installed in moving vessels (ASVs), with previously combined trajectories and this way extending the operational range of the acoustic network. In order to save power, it will have synchronized clock with the acoustic transmitters and use the One Way Travel Time scheme. The mapping system will be a combination of an off-the-shelf MBES with a new long range bathymetry system, with a source on a moving surface vessel and the receivers on board the AUV.

Given the extremely short time for preparation of the system for round one of the challenge, there are many activities in parallel that need to be completed and validated. DART, a deep water AUV, is already under testing in its initial version, which will be followed by deep water testing and integration of the payload sensors. The ASVs are being tuned to travel long distances with accurate trajectories. Many other subsystems are being tested to address the XPRIZE challenges.

We are convinced that the PISCES approach will be a breakthrough in ocean exploration and discovery, not only to undertake the challenges of the XPRIZE competition, but also to extend the operation to larger areas of the oceans. In fact, the envisaged solution is highly scalable, by adding more AUVs to the underwater fleet, or by distributing complete constellations along these larger areas. Moreover, the range of the system is only limited by the finite energy stored onboard. With the emergence of new battery technologies, docking stations or energy harvesting techniques, the concept can easily be extended for basin wide ocean exploration and discovery.

ACKNOWLEDGMENT

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