The MARES AUV, a Modular Autonomous Robot for Environment Sampling

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***Abstract*— In this paper, we discuss the design aspects and the development of the MARES AUV, a 1.5m long vehicle, weighting 32kg, designed and built at the University of Porto, Portugal. This vehicle is highly maneuverable, with the ability to move in the vertical plane, controlling pitch and vertical velocity; forward velocity can also be determined, anywhere between 0 and 2 m/s. MARES can easily integrate any new payload within reason, finding applications in a wide range of areas, such as pollution monitoring, scientific data collection, sonar mapping, underwater video or mine countermeasures.**

I. Introduction

The Ocean Systems Group at FEUP[1]/ISR[2] conducts research activities in robotics and has accumulated expertise in the utilization of AUVs and in the development of particular subsystems. AUV technology is already sufficiently mature and there is a large number of operational systems, in various sizes and configurarions, covering scientific, commercial and military applications [1]. Commercially available AUVs use proprietary subsystems and architectures, so that it is usually difficult to incorporate new devices. Furthermore, there are still opportunities for improvement and so we decided to proceed with a new design, saving on acquisition costs and benefiting enormously in terms of technological know-how.

MARES, or *Modular Autonomous Robot for Environment Sampling* (fig. 1), is a 1.5m long Autonomous Underwater Vehicle (AUV), designed and built by the Ocean Systems Group. The vehicle can be programmed to follow predefined trajectories, while collecting relevant data with the onboard sensors. MARES can dive up to 100m deep, and unlike similar-sized systems, has vertical thrusters to allow for purely vertical motion in the water column. Forward velocity can be independently defined, from 0 to 2 m/s. Major application areas include pollution monitoring, scientific data collection, sonar mapping, underwater video or mine countermeasures.

This paper is organized as follows: in section II, we present the particular requirements for the AUV at the beginning of the project; in section III we detail the solutions adopted for each MARES subsystem, and, in section IV, we present the mission support equipment that was also developed; finally, in section V, we describe a demonstration mission where the AUV was used to find the plume from a sewage outfall, in the Atlantic off the Portuguese coast, in November 2007.

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Fig. 1. MARES AUV with an external CTD.

II. Design Requirements

The design of an Autonomous Underwater Vehicle is a relatively complex task and it is paramount to start by identifying the most critical requirements for the envisaged missions, such as depth rating, battery endurance and payload sensors. The development of the AUV is governed by the combination of these requirements, but taking into account possible constraints in fabrication, assembly and operational logistics.

The main idea behind the development of the MARES AUV was to conceive a platform for environmental sampling in coastal waters, and so we settled on a 100 meter depth rating. There is currently a wide variety of sensors for *in-situ* measurements, with reduced size and power consumption. At the same time, battery capacities are getting higher and there are other emerging technologies for electrical power supply (fuel cells, for example). We then decided to start by relaxing the battery endurance requirement to a few hours, with the belief that in the near future some of these technologies will allow for a considerable increase in energy densities.

This project started in 2006, following 10 years of experience in the customization and utilization of small AUVs in the field for environmental missions [2] [3], which contributed to the identification of some characteristics that this new generation AUV should possess. First of all, the vehicle should have a highly modular construction, in the sense that it should be very easy to to reconfigure (swapping or adding sensors, for example) and at the same time allowing for independent subsystem development.

Naturally, cost is always an important factor, and we were interested not only in diminishing development costs, but also in minimizing maintenance and operational costs. This reduction can be achieved by a modular approach in the overall design and also by the reduction in the size and weight of the vehicle and the necessary mission support equipment.

Mission performance was also considered, and this resulted in the requirement of creating a large library of elementary maneuvers, a simple mission programming and a user friendly interfacing with the vehicle and with all mission support equipment.

Finally, but surely not the least important, overall system safety should be ensured. This includes vehicle tracking capability during the missions, as well as tracking and recovery procedures at the end.

III. The MARES AUV System

MARES configuration can change significantly according to the application scenario, so that it is difficult to define what is a *standard* configuration. In table I we summarize the main characteristics of the AUV version that was demonstrated at sea in November 2007, as can be seen in this papers' photos and diagrams.

TABLE I
MARES MAIN CHARACTERISTICS

Length	1.5 m
Diameter	20 cm
Weight in air	32 kg
Depth rating	100 m
Propulsion	2 horizontal + 2 vertical thrusters
Horizontal velocity	0–2 m/s, variable
Energy	Li-Ion batteries, 600 Wh
Autonomy/Range	about 10 hrs / 40 km

A. Mechanical

All mechanical parts were designed using Solidworks® CAD software (Fig. 2) and machined from polyacetal in a local machine shop, with small parts in aluminium and stainless steel. Polyacetal is a high performance polymer, with a high degree of rigidity and mechanical strength that makes it an excellent weight-saving metal replacement. It is completely corrosion proof and it is readily available in a wide range of sizes of tubes and rods, at reasonable prices.

The vehicle hull evolves around a central watertight cylinder, where all electronic boards are installed, with the battery packs located at the bottom to lower the center of mass. To simplify the design, this is the only watertight enclosure and therefore all other equipment has to be waterproof. The other polyacetal sections are designed to carry wet sensors and thrusters and they are fully interchangeable. This allows for very easy sensor swapping and/or repositioning, or even to test different configurations of thrusters. The main cylinder has 9 holes in each end cap, to accommodate standard bulkhead connectors and at the moment there are still several unused, sealed with dummy plugs.

In order to minimize the power required to change depth, the vehicle weight in water should be zero. In practice, however, it is usually kept slightly negative for safety reasons. Whenever necessary, syntactic foam is machined and inserted in wet compartments to compensate for any new board or device that is installed.

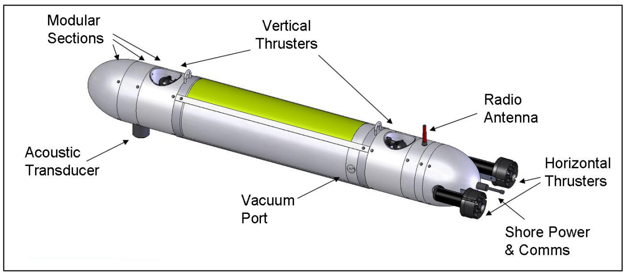

Fig. 2. MARES Solidworks® model.

The overall vehicle shape resembles that of a torpedo, with ellipsoids both at the nose cone and at the tail. This configuration is very simple to construct and allows for the vehicle length to be easily extended, as compared to other hull shapes without constant cross-sections. The central cylinder provides most of the vehicle flotation and it is also possible to increase its length, for example if more batteries are needed.

Typical small-size AUVs use vertical and horizontal fins to adjust heading and pitch, but this requires a minimum forward velocity for the control surfaces to be effective [4][5]. On MARES, four independent COTS thrusters provide attitude control both in the horizontal and in the vertical plane. Two horizontal thrusters located at the tail control both forward velocity and rotation in the horizontal plane, while another set of thrusters, in the vertical direction, control vertical velocity and pitch angle. This arrangement permits operations in very confined areas, with virtually independent horizontal and vertical motion at velocities starting at 0 m/s. This is one of MARES innovations, as it cannot be seen in any AUV of similar size and weight. Furthermore, the modularity of the system allows the integration of other thrusters, for example to provide full control of the lateral motion.

It should be stressed that fins are usually more efficient for diving than thrusters, but with simple fins it is not possible to control pitch angle independently of depth. In mission scenarios where bottom tracking is important, such as sonar or video acquisition, a fin controlled AUV will pitch up and down to follow the terrain, affecting data quality. On the contrary, MARES AUV can control **both** pitch angle and depth independently, being able to maintain data quality even if the terrain has significant slopes.

Another advantage of using thrusters is that all moving parts can be fully shrouded and there are no fins protruding from the hull, which minimizes the risk of mechanical failure. In the end, we deliberately traded some of the efficiency with increased maneuverability and robustness.

B. Power and energy

Most of the power required by an AUV is spent in propulsion, with only a small amount permanently needed for onboard electronics. In MARES, all energy is stored in rechargeable Li-Ion battery packs, currently with a total amount of 600 Wh, at 14.4 V. Battery power is directly available to the motor controllers and, through a set of voltage converters, to the rest of the onboard electronics.

Battery endurance greatly depends on vehicle velocity, both in the horizontal and in the vertical plane. For typical *horizontal missions*, with relatively slow changes in depth, there is sufficient energy for about 8-10 hours of continuous operation (around 20-25 miles or 40 km). These are relatively modest numbers, but they seem to be sufficient for the great majority of envisaged missions. In any case, there is still some available volume for a few more battery packs. It should be stressed that these numbers refer to standard horizontal motion and it is also necessary to account for any significant vertical motion. For example, the vehicle can hover almost motionless in the water column, at a specific depth, but still requiring some small amount of power to provide depth corrections. In this case, the total endurance will be longer in time but relative to a shorter horizontal range.

C. Computational system and onboard software

The onboard computational system is based on a PC104 stack (Fig. 3), with a power supply board, a main processor board, and additional boards to interface with peripherals, such as health monitoring systems, actuation devices, and navigation and payload sensors. A flash disk is used to store both the onboard software and also the data collected during operations.

Fig. 3. PC104 stack in the internal frame.

The onboard software was developed in C++, runs on a Linux kernel and is composed by a set of independent processes. In this way, not only the system modularity and robustness are increased but also its debugging and recovery from unexpected events is much simpler. The communication between the modules relies on the exchange of messages, using the User Datagram Protocol. This allows connectionless data exchanges, with reduced processing overhead, as required in this kind of applications.

The interface with the hardware is managed by dedicated processes that provide an abstraction layer (Fig. 4). The main process estimates the vehicle state in real time and executes the mission plan, which is essentially a list of predefined maneuvers. A black box data logging system registers all data related to the vehicle motion on the flash disk. This system can also be used to register payload data, if necessary.

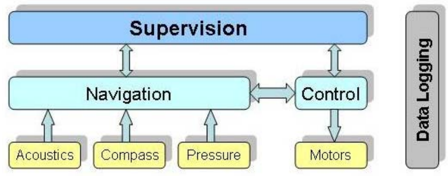

Fig. 4. Major onboard software modules.

A supervision module continuously monitors the behavior of the vehicle and aborts the autonomous operation if safety margins are exceeded or unexpected events occur. This module also establishes a communication link with the mission control station when the vehicle is at the surface.

Payload sensors and systems are typically controlled by dedicated modules. In general, these modules interact with the supervision module, for configuration and communication with the control station, and also with the data logger.

D. Navigation and control

To estimate its position in real time, the vehicle carries a pressure sensor, a digital compass with a set of tilt sensors, and an acoustic system for long baseline (LBL) positioning [6]. This acoustic system is a second generation of multi frequency Rx/Tx boards, developed by the Ocean Systems Group, following some excellent results with previous versions [7]. Vehicle depth is directly given by the pressure sensor and horizontal position is estimated by a Kalman filter that fuses dead reckoning with LBL data [2]. This navigation package assures real time accuracies of about 1 cm in the vertical plane and below 1 m horizontally. Furthermore, all navigation data used by the vehicle is stored in the flash disk and is processed at the end of each mission by a smoothing algorithm to improve the accuracy of the vehicle positioning [8].

The AUV control system is organized into four basic and independent controllers: velocity, heading, pitch and depth. The outputs of the first two controllers are combined to obtain the actuation for the horizontal thrusters, while the outputs of the others provide the actuation for the vertical thrusters. Each controller can operate either in closed or open loop mode. The inputs for all controllers are provided by the guidance systems and depend on the current maneuver that the vehicle is executing.

An AUV mission is a set of elemental maneuvers that the vehicle should execute in sequence. Each maneuver prescribes the behavior of each of the four basic controllers (therefore defining the vehicle motion). It also defines its end condition, and a timeout for safety reasons. Besides some maneuvers that are only used for debugging purposes, the basic AUV maneuvers are:

dive – a downwards maneuver, typically executed at the start of a mission or in depth transitions;

surface – a upwards maneuver, typically executed at the end of a mission or in depth transitions;

hovering – a maneuver that stops the vehicle at the current position;

gotoxy – an horizontal plane maneuver that drives the vehicle along a straight line.

The possibility of independently defining each basic controller allows for very different vehicle behaviors, making the operation of MARES very flexible. For example, a pure vertical motion can be easily obtained by a dive maneuver with a closed loop pitch with zero reference and zero surge command; a combined vertical and horizontal motion can be achieved with a dive maneuver with a closed loop pitch with a negative (downward looking) reference and an appropriate surge command.

Furthermore, each basic controller is already prepared to accept inputs defined by external processes. This allows for the implementation of unconventional guidance strategies which can be based on payload data collected in real time.

E. Payload

The modularity of the vehicle allows for a simple integration of different payload sensors, involving three sub-tasks: mechanical installation, electronics interfacing and software.

Mechanically, a new sensor may be installed in a dedicated section of the hull, if it is relatively small. Alternatively, it can be externally attached to the vehicle body, since there are many fixing points available. In any case, it is important to verify the weight of the sensor (and adapter) in the water, to compensate with extra flotation if necessary. Naturally, the overall vehicle trim has also to be adjusted, particularly in the case of bulky or heavy payloads.

Most of the payload sensors transported by the AUV need energy and a communications link with the onboard computer. MARES has several spare connectors on both end caps of the main electronics compartment, that can be wired to provide power and receive data from these sensors. At the same time, the computational system has spare communication ports, easily configurable according to the payload specs.

As far as software is concerned, the integration of a new payload sensor requires the development of a dedicated software module, known as a *device driver*. Device drivers establish a communication link between the sensor and the onboard software core, allowing for the configuration of the sensor as well as data logging.

Naturally, these tasks are greatly reduced after the first time the sensor is tested. Since then, it becomes very simple to swap payload, just by integrating the proper set: sensor, electronics and software.

IV. MISSION SUPPORT FOR VEHICLE OPERATION

The operation of MARES involves a minimum set of support equipment that we've also designed and developed: buoys with acoustic navigation beacons and a laptop with a communications hub to provide a radio link with the AUV and the buoys.

A. Navigation and Instrumentation Buoys

Navigation and Instrumentation Buoys (NIBs) are moored floating platforms with onboard electronics and energy management system (Fig. 5). The basic configuration includes rechargeable Lead-acid batteries, a compact GPS receiver and a low-power radio modem. NIBs can carry a great variety of sensors and transmit data in real time using the radio link. During the AUV mission, they can work as portable observatories, getting relevant information about the environment (such as current profiles or reference sensor data, for example), to allow for post-mission data processing and interpretation.

Fig. 5. NIB deployed off the portuguese coast.

NIBs are also used as acoustic navigation beacons for the MARES AUV. They have electronic boards to receive and decode acoustic signals sent by the vehicle and respond by transmitting other coded pings into the water. Since they are deployed in known positions, forming an LBL acoustic network [2], the vehicle can determine its own position by triangulation. During an AUV mission, the buoys also relay navigation information back to the mission control station, allowing for vehicle trajectory tracking, following a passive tracking algorithm described in [7].

The GPS location of the NIBs is also monitored and logged throughout the mission, to allow for post-mission corrections of sensor data location, since there may be significant changes of buoy position due to wind and/or currents. Fig. 6 shows the position variation of one of NIBs during a 3 hr operation at sea, with about 30 meters of offset.

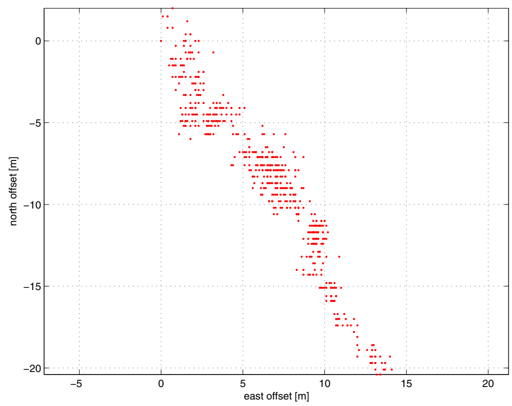

Fig. 6. NIB motion relative to the initial position.

B. Mission control station

In an operational scenario, a mission control station, based in a laptop computer, communicates by radio with the navigation and instrumentation buoys, and also with MARES, while it is at the surface.

A graphical interface running on the control station laptop allows for the configuration of the navigation buoys by selecting interrogation-reply pairs, defining detection level thresholds, etc. Prior to the mission start, this interface can be used to assess the proper operation of the different AUV subsystems. It is also used to issue the mission start command.

During the execution of a mission, the control station receives information from the buoys concerning the acoustic signals exchanged between the AUV and the acoustic beacons and displays in real time (Fig. 7) the position of the AUV.

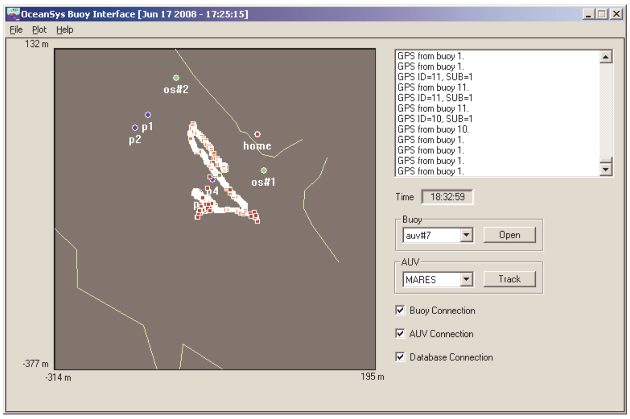

Fig. 7. External tracking of the AUV.

After the completion of the mission, the control station can be used to download the data collected by AUV and to make a preliminary analysis of the mission results. Navigation information from the buoys is fused together with information stored in the onboard logging system to improve the accuracy of the location of the vehicle during the mission. Furthermore, sensor data, collected either by the vehicle or by the navigation buoys, can be reviewed with the help of playback motors to assess vehicle performance and detect undesirable events that might otherwise have been overlooked. This data can also be converted to standard formats for later processing, using Matlab® or other software tools.

C. Typical operation

MARES is very compact and lightweight (32kg), making it easy to transport, deploy and recover from the water by a single person. Depending on the application scenario, it can be deployed from the shore or a small support vessel. If necessary, a line can easily be attached to the top of the hull for launching and recovering from a larger vessel.

A typical MARES mission requires the deployment of at least two LBL multi-channel acoustic navigation beacons in the operation area (with acoustic ranges in the order of 2-3 km). In our own test missions, we have been mooring NIBs (described above) in up to 40 meters of water. Nonetheless, we have also demonstrated the possibility of using virtual moorings or mobile acoustic networks [9].

After waiting some time for the anchor line to settle, the final GPS coordinates of the acoustic beacons are transmitted to the vehicle, together with the rest of the mission script. All this is supported by the mission control station, which is also used to issue the starting signal for the AUV mission.

During the execution of the mission, the control station continuously receives radio data from the navigation beacons, relative to the acoustic signals being exchanged with the AUV. This data is a good indication that the vehicle is navigating as planned and is used to track the vehicle position in real time. To increase operation safety, the laptop interface can also transmit simple special *commands* to the AUV (such as “Abort”, for example) that are sent using the acoustic channel. All this data is stored in the laptop for post-processing, which is particularly relevant in the case of *long* missions, where the beacons position can have significative changes due to currents and/or winds.

At the end of the mission, the vehicle returns to the surface and starts transmitting its own position estimate by radio. This position is obtained by the onboard acoustic navigation system and also from a small GPS receiver located on the hull. All this information is redundant, since it usually confirms the estimate provided by the real time tracking mechanism, but it is important to ensure that MARES (and all data!) is safely recovered by the support vessel.

V. Vehicle demonstration

The first water tests with the vehicle started with a simple hull, as soon as we had enough machined parts to build the main watertight cylinder and install the basic electronics and thrusters. These tests were conducted in a local pool and were useful to validate the integrity of the system, adjust buoyancy and trim, and test simple maneuvers. When we approached the functional version, we moved the test scenario to a reservoir in the Douro river, with a maximum depth of 20 meters, about 30 minutes drive from our lab. We could then proceed with the validation of the remaining subsystems, such as acoustic navigation, until we had a fully functional AUV in the summer of 2007.

MARES was first demonstrated at sea in November of 2007. This demonstration mission took place in the neighborhood of a sewage outfall located 2 km off the Portuguese coast at Foz do Arelho (Fig. 8). MARES was equipped with a Seabird Fastcat 49 CTD and collected 16 samples/second of CTD data for about one hour. Navigation was based on a LBL acoustic network, with two NIBs being deployed about 600 meters apart. During the mission, the buoys transmitted vehicle location data to a small support vessel, so that the AUV trajectory could be followed in real time. At the end, the vehicle surfaced at the pre-programmed location and immediately started transmitting its own position by radio.

Upon vehicle recovery, CTD data was analyzed to infer the location of the sewage plume in the vicinity of the diffuser.

Fig. 8. MARES starting a mission off the Portuguese coast.

Fig. 9 shows a salinity map produced from CTD data, and although the salinity signature was very weak, it was also very consistent. This demonstrated the potential for detecting minute anomalies with the onboard CTD, which was the main objective for this mission at sea. It also served as an operational preparation for a longer mission being planned for the summer/autumn of 2008, under a project with Águas de Portugal (a public company managing water supply and wastewater treatment). In this project, MARES configuration will include scattering and fluorescence sensors, along with the CTD. At the end, all this data will be correlated with complementary information from ship-borne sensors and from dispersion models, to fully map the plume emanating from the sewage outfall.

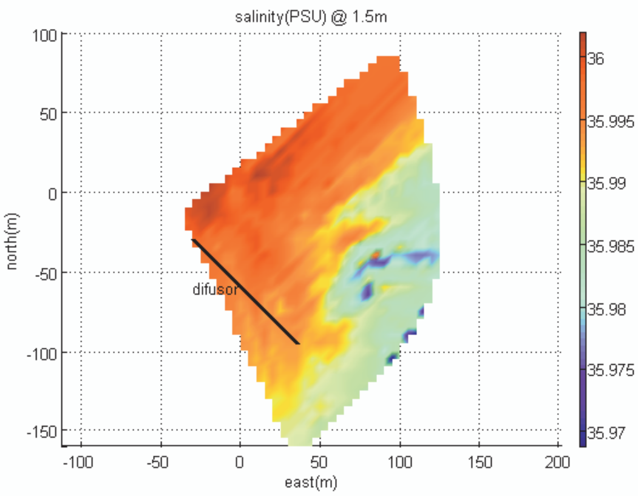

Fig. 9. Salinity map close to the sewage outfall diffuser.

VI. Conclusion and future work

The success of the demonstration mission at sea proved that the initial requirements and the design decisions contributed to the development of an operational vehicle that can be effectively used in real application scenarios.

Overall, the mechanical design has proved to be robust. The vehicle has been transported for field tests in the trunk of a car tens of times with no mechanical failures.

One of the major advantages of the MARES AUV, when compared with other AUVs of similar size, is the ability to control independently the motion in the vertical and in the horizontal planes. This allows for some new primitives of motion, such as commanding the vehicle to be completely motionless in the water column (for example, waiting for some triggering event).

Currently, we are installing a ECO-Puck Triplet sensor, from Wetlabs, that will measure scattering and fluorescence (Chlorophyll and CDOM). Together with CTD, this data will allow the vehicle to map the plume emanating from a sewage outfall, in a mission scheduled for later in the summer. This new payload is being physically integrated in an extra section, following a procedure described in section III-E.

In the near future, we plan to broaden the range of possible missions with MARES, by integrating a sidescan sonar and a video camera. We are also implementing new motion primitives to test unconventional guidance techniques, such as *adaptive sampling*.

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