TriMARES – a Hybrid AUV/ROV for Dam Inspection

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***Abstract*— This paper describes the full development process of TriMARES, a hybrid AUV/ROV designed to fulfil the requirements of a consortium for the inspection and periodic monitoring of a large dam reservoir. The demand of robotic systems for underwater operations is growing exponentially and there are many scenarios for which the commercial solutions are not adequate. Such was the case with TriMARES, where it was possible to take advantage of previous designs to achieve a custom solution in a short time. We describe the initial requirements for the underwater system, we present the main solutions adopted for the vehicle subsystems, and we provide some data from the first in-water tests, performed only 6 months after the beginning of the project.**

I. Introduction

There are many companies providing off-the-shelf remotely operated vehicles (ROVs) and a few other exploiting the market of autonomous underwater vehicles (AUVs). However, the demand of robotic systems for underwater operations is so wide that there are many scenarios for which the commercial solutions are not adequate and a custom solution has to be sought.

The robotics unit at INESC Porto develops custom solutions for specific engineering problems, and it was contracted to provide an unmanned system for the inspection of a large dam in Brazil and for the periodic monitoring of the dam reservoir.

TriMARES (fig. 1) is a 3-body unmanned underwater vehicle with significant payload capability, including high quality video and sonar. The physical arrangement ensures motion smoothness for improved quality in payload and positioning data. TriMARES motion is provided by seven independent thrusters, with no control surfaces, resulting in the ability to hover in the water column, to navigate close to the bottom, or to perform close-up inspections of underwater structures. TriMARES is a hybrid vehicle, since it may be programmed for autonomous missions as a standard AUV or, alternatively, it can be operated as an improved ROV with a cable attached for realtime data transmission. In this paper, we discuss the design aspects and the development of the TriMARES AUV/ROV: we start by describing the main requirements at the beginning of the project, we detail the solutions adopted for the main subsystems, and, finally, we present experimental data from the first in-water trials.

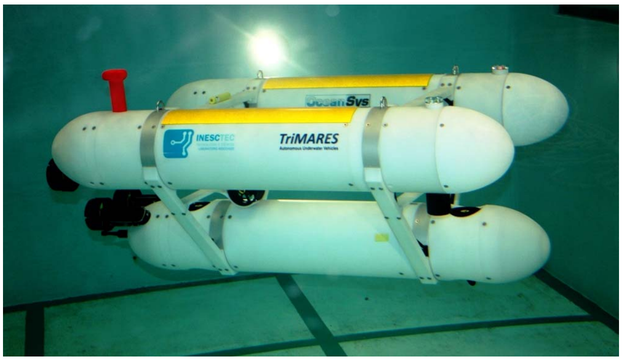

Fig. 1. The TriMARES hybrid AUV/ROV during water trials.

II. Main Requirements

For the successful design of any complex systems, it is paramount to start by clearly identifying the most critical requirements. In the case of underwater robotic vehicles, these are usually dictated by the envisaged missions, such as depth rating, battery endurance, payload sensors, maneuverability, communications and user interface. The main design decisions are then determined by a combination of these specifications, together with possible constraints in fabrication, assembly and operational logistics.

In the case of TriMARES, the main requirements were detailed by the contractor in terms of functionalities and logistics, and can be summarized as:

- Detph rating of 100 meters
- 5 DOF (surge, sway, heave, yaw, pitch)
- Hovering capability
- Forward velocity of at least 1m/s
- Absolute position error below 2 meters
- Autonomy of 10 hours
- Prepared for integration of payload sensor package: video and still camera, sonar, water quality sensors

In order to actually design and build the vehicle, these were mapped into engineering constraints, such as maximum weight and dimensions, degrees of freedom, propulsion power, computational power and navigation sensors.

The vehicle should have a modular construction, being easy to reconfigure and allowing for independent subsystem development. Naturally, cost is always an important factor, and we were interested not only in a reduced development cost, but also in reduced maintenance and operational costs, which is particularly relevant when the end user is not the developer. This reduction can be achieved by the modular approach in the overall design and also by adopting simple, repeatable shapes, and using off-the-shelf materials and components as much as possible. As far as operational aspects were concerned, one of the challenges in the design was that the vehicle should be able to work both as a *standard* AUV, for reservoir monitoring, or to have a cable enabling high throughput data transmission, during inspections. This ROV-like operation should also be supported by hidden autonomous behaviors to help a non-specialist pilot, like auto-depth, auto-heading, etc.

Finally, but not less important, system safety should be ensured, with vehicle tracking capability during the mission and tracking and recovery procedures at the end.

III. The TriMARES Vehicle

After a few months of discussions with the contractor to decide possible design trade-offs, the contract with INESC Porto was signed in the summer of 2010, and it included the delivery of one vehicle to the Brazilian consortium, followed by local training and support, and a partnership with a Brazilian research institution for the use and development of the monitoring system during a second stage of the project. Although the configuration of TriMARES can change by the inclusion/replacement of specific modules, the characteristics of the vehicle that was shipped to Brazil are summarized in table I.

TABLE I
TriMARES main characteristics.

Length	1.3 m
Overall width	80 cm
Overal height	50 cm
Weight in air	75 kg
Depth rating	100 m
Propulsion	4 longitudinal thrusters 2 vertical thrusters 1 lateral thruster
Horizontal velocity	0–1.5 m/s, variable
Energy	Li-Ion batteries, 800 Wh
Autonomy/Range	about 10 hrs / 40 km

Mechanical Structure

The design of TriMARES was based on previous experience with other vehicles, namely with the MARES AUV [1]. MARES is a small size torpedo shaped AUV, with a central watertight cylinder containing batteries and electronics, and several stackable cylindrical sections attached to both sides, including the thruster arrangement. It was developed in 2006 at the University of Porto, in Portugal, and has been in routine operations since 2007, mainly for environmental monitoring. Although the configuration of MARES is extremely useful for a wide range of application scenarios, it was clear that this project required a larger vehicle, to accommodate more energy and large sensors. In any case, we took advantage of the modularity of MARES to reutilize many of the section designs and, this way, speeding up the overall project.

For the configuration of this new vehicle, we chose a multiple body structure, which provides much space for electronics and payload, while still ensuring good hydrodynamics and reduced weight. A similar configuration has been developed as long as 20 years ago, with the ABE vehicle at WHOI [2], and recently there have been a few more examples of multiple hull designs, but most of them with much larger weight and dimensions as compared to TriMARES [3]–[5].

The TriMARES' mechanical arrangement follows a modular approach, with three similar bodies linked by a light mechanical structure, which also serves as cable ducting and protection. Each body is built around a 20cm diameter, 50cm long watertight cylinder, to hold batteries, computers and other electronics. The interface with the external subsystems is done through the end caps, each having 9 holes to accommodate standard bulkhead connectors. Each cylinder has also a vent plug that can be removed to avoid gas build up during battery charge, and where a vacuum pump may be connected to confirm sealing. Both the cylinders and end caps were machined from polyacetal copolymer (POM) and designed to withstand 100 meters of pressure. POM 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.

Attached to the end caps, a set of aluminum rings is used to provide lifting points and to hold the bars connecting the 3 bodies, forming a triangular shape with 80cm of overall width and 50cm of height. This separation is not only physical but also functional. The rechargeable batteries and the power management system are the heaviest part of the vehicle and are located in the bottom cylinder, to lower the center of mass and increase the separation with the center of buoyancy. The top-starboard cylinder holds the main computer, the navigation sensors and the main communication devices. Finally, the payload system is located in the top-port cylinder, with all interfaces for the payload sensors and a second computer to provide realtime processing of sensor information.

All other sections are built with flooded stackable rings, also in POM, with the same outside diameter (20cm), therefore ensuring a continuous profile. They are designed to carry wet sensors and thrusters and since they all have common mechanical interfaces, they are fully interchangeable. This allows for very easy sensor swapping and/or repositioning, or even to test different configurations of thrusters. Finally, each body terminates with ellipsoid-shaped ends, both at the nose cone and at the tail. These are used as a thin shell to reduce vehicle drag and were manufactured in fiberglass from a mould to reduce fabrication cost.

In order to minimize the power required to change depth, the vehicle weight in water should be zero, i.e., the dry weight should equal the weight of the displaced volume of water. In practice, however, it is usually kept slightly negative for safety reasons. A set of syntactic foam parts, with a density of 200kg/m^3, were machined and inserted in wet compartments to ensure the trimming of the final solution. Extra buoyancy modules and corresponding ballast weights were included to compensate for any new board or device that is installed.

All mechanical parts were designed using Solidworks CAD software (fig. 2), which allowed for an early visualization and validation of the full system, long before the actual parts were available. As far as fabrication was concerned, the simplest/smallest parts were machined in house, while larger and more precise parts (like o-ring grooves and watertight containers) were ordered from a local machine shop.

Propulsion

The vehicle required not only a great number of thrusters to ensure maneuverability (5 degrees of freedom), but also enough power to overcome the relatively large drag. Even though the power requirements are clearly higher for the forward direction to ensure a useful velocity during reservoir surveys, we decided to use the same thrusters for all directions, to minimize the number of different parts. From our previous experience, we use small off-the-shelf thrusters from Seabotix, based on brushless DC motors, providing a nominal thrust of 35N, with possible transients up to 45N.

One of the requirements for this project was for the vehicle to be able to hover in the water column, in order to approach the bottom of the reservoir and to enable close-range inspection of the underwater features. The vehicle is inherently stable in pitch and roll due to the large separation between the center of mass and the center of buoyancy. However, the pitch control can be helpful during the mission, to provide a straight trajectory between two waypoints at different depths, or to simulate a tilt motion of the camera. In order to achieve this, TriMARES has two through-hull vertical thrusters, located in the bottom body. Since they are aligned with a vertical symmetry plane, they can be used to control both heave and pitch simultaneously, with minor influence on the other degrees of freedom.

Horizontal propulsion and direction are controlled by four independent thrusters located at the stern, one at the rear end of each of the top bodies, and two in the lower body. With each thruster providing a nominal force of 35N, this arrangement enables much more power than required to move the vehicle at 1 meter per second, as desired. In any case, this ensures some degree of redundancy, and allows for a proper operations even in the case of a fault, following the approach in [6]. Furthermore, we can take advantage of their location in different vertical layers to provide a different mechanism of thruster allocation to provide pitch control together with surge control.

Finally, a single lateral thruster was also installed to control sway control. This thruster is located close to the center of mass so that the effect in the other degrees of freedom is minimized.

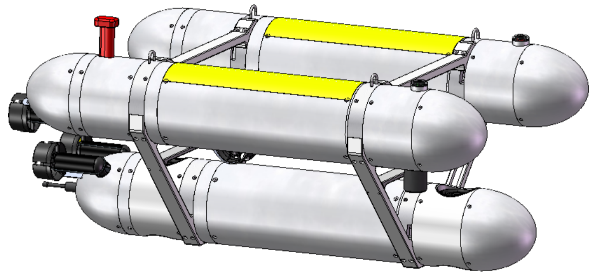

Fig. 2. TriMARES Solidworks model.

Power Management

Vehicle energy is provided by rechargeable Li-Ion batteries located in the lower pod, with a total energy of 800 Wh. Depending on vehicle velocity and payload requirements, these batteries can last up to 10 hours, corresponding to about 40km. In the same cylinder, the vehicle is fitted with an intelligent power management system which is capable of handling all aspects of battery charging and system powering. In addition, it provides fully configurable power protections as well as overall battery health status report via an RS232 connection with the main onboard computer. This allows to continuously monitor parameters like power flow, power balance and individual battery temperature. The overall power distribution can be seen in figure 3.

To charge the vehicle, a custom 320W DC power supply is used. A commercial power supply was fitted with specially designed resettable power protections along with an underwater power cable compatible with the vehicle. With this power source, the batteries can be fully charged inside the vehicle in approximately 3 hours. The power management system is capable of simultaneously charging the batteries and supplying power to the vehicle electronics, which allows for immediate downloading and processing of data after mission completion. In order to prevent accidental gas accumulation during battery charge, and following the manufacturer's recommendation, the charging procedure is not allowed without ventilation of the lower pod, which can be done by opening a vent cap placed in the top of the pod. This vent cap has an embedded magnet and, inside the pod, a charge monitoring board detects both the absence of the cap through a magnetic switch and the presence of an external charger. If the conditions are fulfilled, the charge is allowed, otherwise it isn't and an acoustic warning is emitted.

Raw battery power is divided in the lower pod into a 500W DC/DC converter and a power distribution board for the other cylinders. The DC/DC converter is used to step up the battery voltage level (about 14.6 V) into the 28 Volts needed for the thrusters. After conversion, this higher voltage

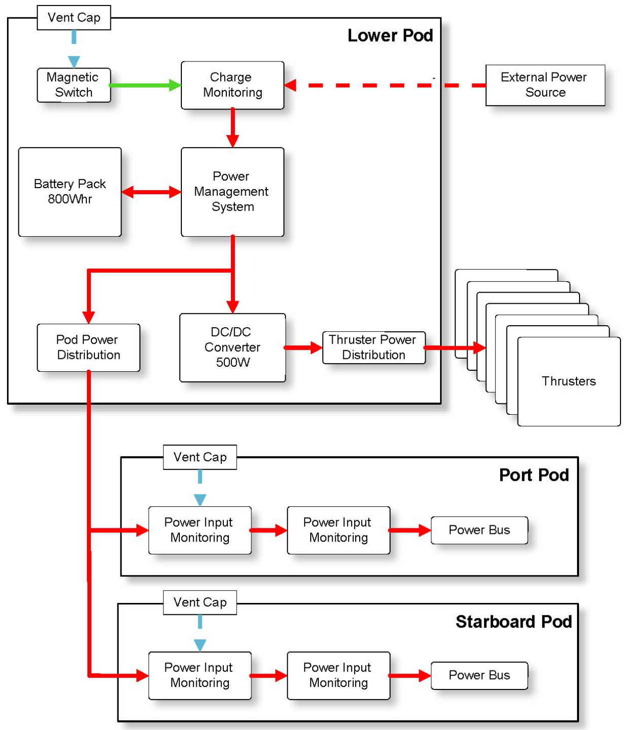

Fig. 3. Power distribution in TriMARES cylinders.

bus feeds a thruster power distribution board, fitted with individual resettable current protections, where all the thrusters are connected. The pod power distribution board switches raw battery power for the two upper pods and it is also fitted with individual resettable over current protections.

The power is carried to the upper pods through underwater cables hidden within the mechanical frame bars. When entering each of the top cylinders, a DC/DC converter steps the voltage to the levels required by the various equipment.

Computational Systems and Onboard Software

TriMARES computational system is composed by two independent computers. The main computer is located in the starboard pod and is based on a PC104 stack, with a power supply board, a main processor board (with AMD Geode LX800 processor at 500 MHz), and additional boards to interface with health monitoring systems, actuation devices, navigation sensors, and communication systems. The on board software runs on a Linux kernel and both the operating system and the on board software are stored in solid state disk. TriMARES software is composed by a set of independent processes to increase software robustness and modularity, following an architecture similar to the one employed for the MARES AUV [7]. The low level processes make the interface with the hardware providing an abstraction layer. On top of them, several other processes take care of specific tasks: position estimation, feedback control, autonomous mission execution, interface for external operation, vehicle supervision and health monitoring, and data logging. Interprocess communication relies on UDP messages and the main feedback control loops run at 10 Hz, with an overall CPU load less than 20%.

The second computational system, located in the top-port body, deals with payload sensors and communicates with the main computer through an ethernet connection. It is also based on a PC104 stack, with a frame grabber to digitize the video from the camera, and the interface with electronics for the sonar transducers. This secondary system can be fully programmed by system users for payload interfacing, processing, and logging, without affecting the normal operation of the modules running in the main computer. This way, system architecture is kept open without putting in risk robustness. It should be noted, however, that the secondary system can take control of the vehicle by sending appropriate commands to the external operation interface running on the main computer. This possibility is essential for the execution of adaptive sampling missions. The communication network of TriMARES is depicted in figure 4. When at surface the vehicle can communicate with a shore station using the WiFi link directly connected to the main computer. Internally, an ethernet switch is connected to both computers. A specially configured network bridge running on the main computer assures a transparent connection between the secondary computer and the shore station through the WiFi link. The switch is also connected to an ethernet optic transceiver to enable communication with the vehicle through a fiber optic umbilical (ROV operation). Although not present in the base version, the system is already prepared for other communication channels, namely a long range UHF radio link at the surface or an acoustic system for underwater communication. In both cases, the link is directly established with the main computer.

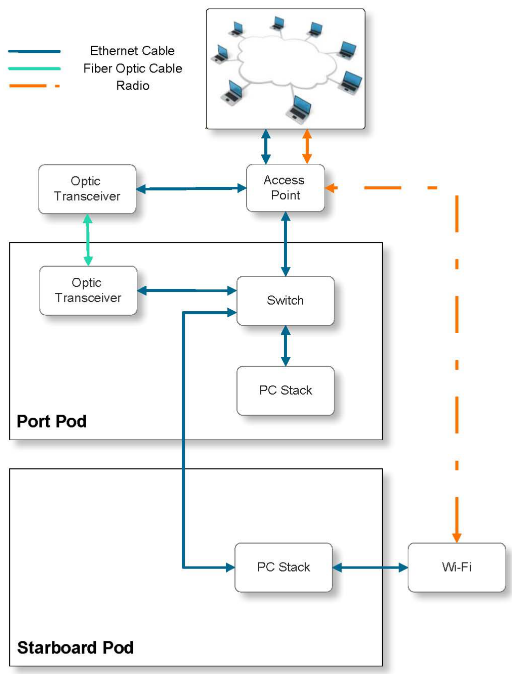

Fig. 4. Network connections in TriMARES cylinders.

Navigation and Control

Geo-referenced positioning relies on a LBL acoustic network with at least two moored beacons for determination of the vehicle horizontal coordinates and a pressure cell to estimate depth. The vehicle also carries an integrated set of 3D accelerometers, rate gyros and magnetometers for estimation of global attitude (roll, pitch, and yaw). To surpass the low update rate of the LBL range measurements (typical full update cycles last more than 3 seconds) an online interpolation mechanism based on an extended Kalman filter is employed. This process runs at 10 Hz and fuses acoustic range measurements with thruster RPM, vehicle attitude and depth, and other inertial data, to produce real time estimates of the vehicle position. Raw sensor data is logged to allow for post mission accuracy enhancement by smoothing algorithms.

The control system was designed so that the controllable DOFs (surge, sway, heave, pitch and yaw) can be controlled independently either by setting position or velocity references. Such method allows for controlling the horizontal position or surge velocity independently of the depth, pitch or yaw, yielding greater flexibility and versatility of the TriMARES motion. Based on nonlinear control tools, the elementary motions are truly decoupled by compensating the strong cross-relations found in this type of mechanical shape. This characteristic allows the end-user to perform any type of composed motion without having to be concerned with the low-level control nor the intrinsic complex dynamics. To illustrate the idea, suppose that we are interested in performing an elaborated trajectory in the horizontal plane which may involve position and velocity – typical trajectory tracking, for instance. However, the depth must remain constant over the operation and the pitch must be different from zero (e.g., nose pointing toward the seafloor). Such task is made possible by setting the depth and pitch references constant, while the rest of the DOF references remain available and ultimately set by an external entity (this type of motion is particularly interesting for ROV mode operation).

As it could be preferable defining position or velocity references given in different referential frames, we consider two possibilities for each of the DOFs: inertial, earth-fixed reference frame and body-fixed reference. The control laws were derived in order to meet some essential requirements:

- Ability to move according to position references given in the earth-fixed frame.
- Possibility of setting velocity references in the earth-fixed frame.
- Capability of accepting velocity reference in the body-fixed frame.

The task of deriving control laws that satisfy such requirements is not trivial and becomes more complex when the motion along the different axes is intended to be decoupled. The complexity mainly arises from the hydrodynamic coupling effects.

Our approach makes use of the nonlinear control theory, implementing the backstepping method [8] to achieve robust and accurate control of the TriMARES vehicle. This nonlinear control tool has already proven to be effective in our previous works on other vehicles [6], [9]. Let us describe the main procedure of derivation of the controllers: first, an error vector is defined as the difference between the current position and attitude vector p and the position and attitude vector p_{ref}, $e_p = p - p_{ref}$; a quadratic Lyapunov function is defined based on the error:

$$V = e_p^T e_p. \tag{1}$$

At this stage, velocity references ν_d are derived in order to make the time derivative of the Lyapunov function negative definite $\dot{V} < 0, \ \forall ||e_p|| \neq 0$. Subsequently, the velocity externally generated are included in ν_d – note that each of the several DOFs can only be controlled in position or velocity mode. Then, a new, augmented Lyapunov function is defined as a quadratic function of the velocity error $e_\nu = \nu - \nu_d$

$$V' = V + e_\nu^T e_\nu. \tag{2}$$

The time derivative of V' is made negative definite by appropriately choosing the actuation assigned to each thruster.

Although this method provides satisfactory results, its performances are strongly related to the mathematical model of the hydrodynamics. Therefore, a reasonably accurate 6 DOFs model was previously estimated to be integrated in the control law.

Payload

TriMARES was designed to accommodate a high resolution video and photographic camera, a bathymetric sonar, and a water quality sensor package. However, the modularity of the vehicle allows for different other payload sensors that can be carried within dedicated sections of the hull or externally attached to the vehicle frame. Such integration involves not only the mechanical aspects, but also the necessary interfacing in terms of electronics and software. In case of necessity, extra flotation modules may also be included to trim the overall vehicle and maintain neutral buoyancy.

Vehicle Operation and Safety

TriMARES is relatively compact, weighting approximately 75kg. The deployment and recovery can be made by a support vessel, preferably with a small crane, or the vehicle may be launched from an access ramp and towed to the operation area.

A typical TriMARES mission requires the deployment of at least two LBL acoustic navigation beacons to provide absolute geo-location of measurements during dives [10]. The configuration of the vehicle and the navigation network, as well as the mission programming, are made with the aid of a graphical interface running on a laptop computer. A wireless network links the laptop, the navigation beacons and the vehicle while it is at the surface, using a combination of WiFi and UHF radio communications, to ensure high bandwidth and long ranges. During the execution of an AUV mission, the graphical interface also receives data from the navigation beacons allowing for the real time tracking of the vehicle position. To increase operation safety, the laptop interface can also send simple special commands to the AUV using the acoustic navigation network.

The onboard power consumption is always monitored by the main CPU and there are several levels of protection against over current. On a first level, the thruster driver receives a periodic status report from each thruster indicating a proper behavior. Next, the onboard software ensures that the motion controllers never provide thruster commands that exceed the limits of the thrusters and of the underwater cables and connectors. Finally, the thruster allocation is also performed in such a way as to avoid exceeding the total amount of power provided by the DC/DC converters.

Further safety measures include leak detectors in all cylinders, localization lights, and an independent continuous pinger from Sonotronics.

IV. In-Water Trials

The first water tests with the vehicle were carried out in a 5mx5m test tank, in our own facilities. Given that the vehicle has hovering capability, even such a small tank is enough to perform many initial tests, from the validation of the main subsystems and ballasting, at the very beginning, to depth control and programming of simple maneuvers and missions.

When we approached the functional version, we moved the test scenario to a reservoir in the Douro river, with a maximum depth of 15 meters (fig. 5). This scenario was chosen not only because it is close to our lab, but also because it is a scaled down version of the final application scenario for TriMARES, in Brazil. During these tests, we have trained the launch and recovery procedure and we have also tested the performance of the combined GPS-WiFi antenna located at the stern of the starboard pod (see figure 5). Even with a small height above the surface of the water, it was possible to maintain a WiFi connection more than 200 meters away, using a sectorial antenna at the control station, and the vehicle would get a GPS update only a few seconds after emerging. Although the acoustic navigation system is still being developed, we had the chance to use a prototype for tracking the vehicle location during a few simple missions, and also to test the emergency ”abort” command, sent acoustically by a navigation buoy deployed nearby.

Finally, we have programmed the vehicle to carry out a few simple missions, like following a sequence of waypoints, or hovering at a certain depth. These missions were useful to validate the mission control software and also to tune the hydrodynamic model of the vehicle, in order to improve the performance of the controllers. These models are commonly difficult to derive due to their intrinsic complexity and large number of parameters. Moreover, hydrodynamics literature mainly relies on semi-empirical formulas to derive those parameters and some characteristics such as roughness may be difficult to assess [11], [12]. Several experiments were therefore carried out to infer about the overall model as well as validating the control law which strongly depends on it.

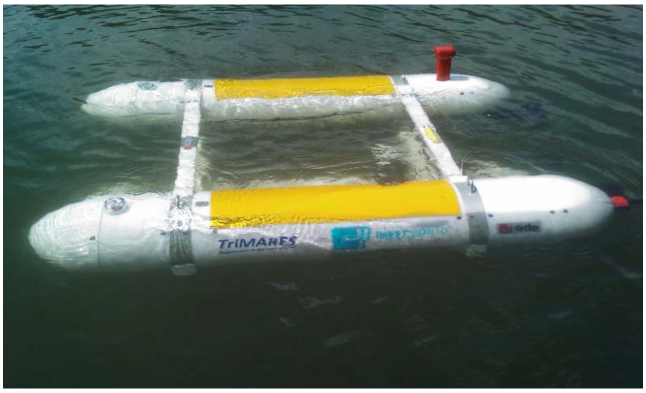

Fig. 5. TriMARES ready for testing in Douro river reservoir, June 2011

While relying on a previously derived thruster model, most of the experiments were conducted in order to quantify viscous damping due to the motion along the various axes, thus leading to a practical estimate of opposite forces along surge, sway, heave, pitch and yaw. Such task has introduced minor adjustments in both the model and the control law.

Figure 6 shows an example of depth and pitch control during a dive to a depth of 5 meters. The vehicle starts descending to a depth of 2 meters at approximately $t = 530$s, changes depth reference to 5 meters at $t = 560$s, and switches off the vertical controllers at $t = 650$s. Note the negligible steady state oscillation in depth when the vehicle stabilizes at 5 meters (the amplitude of the oscillation is below 2 centimeters), demonstrating the robustness and the accuracy of the control approach. Such capability is particularly interesting for inspection tasks, such as video recording, and it may even be explored for intervention operations. Although the pitch angle is always small, it is clear the influence of the surface and the natural damping after the controllers were switched off.

Conclusions and Future Work

The first in-water trials of TriMARES started only 6 months after the meetings with the end-user when the functional requirements were discussed. This was only possible due to the earlier experience with other vehicles, with a well planned project, and keeping a tight control of the progress of the project, particularly in what concerned orders of critical components. Also important for the rapid development of the final stage was the availability of a small test tank in our facilities. The successful accomplishment of the trials demonstrates that the engineering requirements were met and the design decisions contributed to the development of an operational vehicle adequate for the planned tasks. Furthermore, we think that the modularity and versatility of the system may be further exploited, so that the TriMARES range of vehicles may be used in many different applications and in several scenarios of operation.

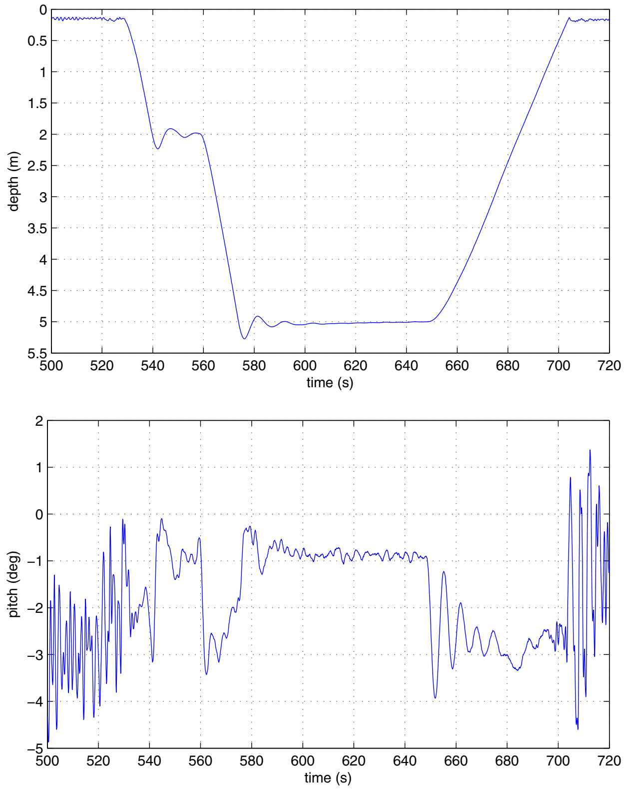

Fig. 6. Depth and pitch control of TriMARES.

For the near term, we will proceed with training of the Brazilian partners on vehicle operation and maintenance, as defined on the contract. We will also provide support in the next phase of the project, with the integration of the acoustic navigation system and payload sensors, so that the full system may start gathering operational data in the beginning of 2012.

Finally, with the development of automated vision processing, together with increased navigation accuracy, we are planning to extend the TriMARES features, not only to be able to work as an advanced inspection platform, but also to include some intervention capability.

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