DART – A Portable Deep Water Hovering AUV

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***Abstract*—Autonomous Underwater Vehicles are remarkable machines that revolutionized the collection of data at sea. There are many examples of highly operational man-portable vehicles for shallow waters, but there was no similar solution for deep water operations. This paper describes the development of a portable, modular, hovering AUV for deep water operations. The vehicle has little over 50kg, 2.4m of length, and a depth rating of 4000m. The first version of the vehicle has been assembled, it has gone through the initial tests in water tanks, and it is being prepared for the first operations at sea.**

I. Introduction

In the last decades, Autonomous Underwater Vehicles (AUVs) have left the academic environment to become ubiquitous tools for sampling the oceans. The widespread adoption of this technology has been stimulated from the enormous amount of data that could be retrieved, at reasonable operation costs. At the same time, the demand served as a catalyst for further market solutions, at reduced production costs. This escalation has been most visible in shallow water scenarios, not only because of the priority given to coastal operations, but also because of the less demanding engineering challenges. Part of the success of AUV-based operations can be attributed to the large number of existing *man-portable* vehicles. Not only these vehicles are small and lightweight, but also (and probably mainly), because all the logistics associated to their operation are simpler, as compared to their larger counterparts. Unfortunately, the same trend was not seen in deep-water AUVs, with the smallest of these still weighting in more than one hundred kilos. When the deep water scenario is far from shore, the support vessel and all onboard machinery are already prepared for handling heavy loads, consequently there is not a strong drive to reduce size and weight of equipment. In these cases, the preference goes to the robustness (sometimes falsely) provided by larger, heavier systems. However, there are other cases where the ocean reaches thousands of meters of depth within a few kilometers from shore, and it would be beneficial to be able to use smaller, low logistics robotic assets.

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. This paper describes the development of DART (*Deep water Autonomous Robotic Traveler*), a portable, modular, hovering AUV for deep water operations. This vehicle has been designed taking advantage of a modular architecture for underwater vehicles, that has been developed for more than 10 years. It has served to assemble multiple shallow water vehicles and configurations, and now have been extended to include deep water solutions.

The paper is organized as follows. Section II provides an overview of the main efforts that have been made to develop modular, low logistics AUVs for deep water operations. Section III summarizes explicitly the main requirements for the development of this new AUV. Section IV details the components of DART, both in terms of mechanical arrangement and also in terms of electronic subsystems and onboard software. Section V describes the Launch and Recovery System designed for the vehicle and, lastly, Section VI present some concluding remarks and future improvement directions.

II. Related Work

Although there is not a clear boundary between *shallow* and *deep* waters, it is a common understanding that shallow water operations mean a maximum of 100–200 meters of depth (typical of coastal waters), while deep water usually refers to a few thousands of meters. The logistics requirements for operations at sea augment with the size of the equipment and all existing AUVs designed for deep water operations are relatively *larger* and *heavier* than their shallow water versions. The main reason for this comes from the necessity to isolate all electronic systems from water and the need for the pressure housings to withstand extreme values of hydrostatic pressure. This justifies the extra thickness of the housing walls and the use of stronger, denser materials, not only to install the vehicle electronics, but also for all sensors that are in direct contact with water. In order to compensate all this added weight, it is necessary to add flotation material that may take a significant volume. Note that this extra volume also results in an increase in drag, requiring more powerful thrusters and more energy for the same motion patterns.

A popular alternative to house electronics and withstand deep water pressure is to use glass spheres instead of the more typical metallic tubes. Glass has a strength to weight ratio comparable to metals, with a much less cost to manufacture and other advantages such as corrosion resistance, electrical isolation and transparent walls that facilitate visual inspection. Glass spheres have served to host the electronics of the earlier AUVs in the nineties, such as the Odyssey vehicles [1] or the Autonomous Benthic Explorer (ABE) [2], specifically designed for the exploration of the benthic habitats. One inconvenient of glass spheres is the difficulty in installing

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electronics in the round interior, and the need to increase the diameter also to increase the buoyancy to weight ratio. This results in typical solutions using spheres with tens of centimeters of diameter, increasing the overall size and weight of the AUVs (around 200kg in the case of the 3000m rated Odyssey IIb, and 450kg for the 4000m rated ABE).

Another concept that has been suggested a long time ago is to use pressure tolerant electronics (PTE), *i.e.* systems and components that are protected against the pressure and do not require a specific enclosure [3]. A typical solution is to isolate the electronic systems from seawater with an oil bath or an epoxy coating, but it results in greater difficulties in servicing and the components have to be chosen very carefully to ensure that they maintain the same characteristics in high pressure as compared to ambient pressure [4]. For these reasons, the practical examples are still limited to specific subsystems.

In terms of modular deep water AUVs, a good example is the Gavia AUV, originally developed by Hafmynd ehf, in Iceland, and now Teledyne Gavia ehf. Gavia AUVs are assembled from a set of interchangeable modules with 20cm of diameter, that include battery, navigation and payload sensors. The suite of available sensors has been continuously expanding, to accommodate newer systems or functions, such as described in [5]. They result in very compact systems for a wide range of surveys, but the maximum depth rating is only 1000 meters, with a vehicle configuration exceeding 100kg.

Due to the extra physical space required for module interfacing, it is more common to find modular designs in larger vehicles, such as the case of the AUVs from Bluefin Robotics, for example, with a 4500m rated versions exceeding 700kg. Bluefin AUVs are assembled from multiple pressure vessels surrounded by a flooded fairing, and similarly to the Gavia AUVs, their subsystems may be swapped in the field. The modularity has also been explored to the development of additional modules for integration in the portfolio of available options [6].

In our case, we have been concentrating in the development of a modular architecture for underwater vehicles, for more than 10 years, as described in [7] and [8]. This has served to assemble multiple shallow water vehicles and configurations, for example, the MARES AUV [9] and the TriMARES hybrid AUV/ROV [10]. We relied on the modularity of this architecture to replace the pressure sensitive components and achieve a deep water configuration compatible with other existing modules.

III. Main Requirements

One of the main advantages of portable vehicles is the reduced logistics associated with their operation, with an obvious impact on operational costs. As a side effect, it also accelerates the development phase, since it allows for partial/incremental validation of subsystems in field trials. We have been experiencing this in the 10 years of experience in the utilization of the MARES AUV in shallow waters. For this reason, our main requirement for the development of this new AUV was to extend the capabilities of the MARES AUV to deep water operations. Ideally, the AUV should be deployed and recovered using a simple RHIB and reuse as many designs as possible from the earlier modules available for MARES. These include both physical parts and also software and control systems. The mechanical modules include stackable, interchangeable sections with a diameter of 200mm, to install multiple sensors and actuators, and to propagate the male/female connection system. They also include termination modules, or end sections, and pressure housings (see fig. 1 for examples of available designs).

Fig. 1. Example of stackable AUV modules with 200m diameter. These include pressure housings, flooded extensions, and end sections.

So far, all pressure housings have been designed for shallow water, up to 200m of depth, so the main requirement was to design a new pressure housing for deep water operations, and maintain, as much as possible, mechanical compatibility with the other sections. Note that the compatibility has other advantages apart from speeding up the development and facilitating maintenance. For example, it enables the use of many support equipment for different vehicles. One example is the possible use of wireless power transfer systems, or the docking station described in [11].

The development of DART started at about the same time that the "Shell Ocean Discovery XPRIZE" was launched, 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 the concepts that have been planned. Therefore, INESC TEC has registered for the challenge and the DART AUV was planned to be a major asset in the overall solution (see [12] for the details of the full system under development). This participation also served to define some of the requirements that the AUV should have, for example, the maximum depth rating of 4000 meters.

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

In summary, the main requirements and guidelines in terms of components and characteristics were:

- operate in deep waters, up to 4000m of depth;
- conform with the 200mm diameter mechanical sections, reusing designs as much as possible;
- limit size to 2.5 meters of length;
- limit dry mass to 80kg;
- use the same software for mission programming and data playback as with MARES;
- use similar navigation algorithms as with MARES;
- incorporate safety features (leak, battery level, temperature).

IV. The DART AUV

Figure 2 shows a schematic overview of the first version of DART. The vehicle has slightly over 50kg of dry mass and a total length of 2.35m, and has the ability to incorporate payload sensors up to about 5kg in water, without major changes in size. The next sections will describe the main subsystems.

A. Mechanical Structure

As indicated in the requirements, the overall mechanical structure is based on the modular building blocks earlier developed for shallow water vehicles. The modules were designed with a matching, repeatable, male/female coupling system, following a sectional modular architecture, which means that each section can be attached to each other in any order, extending the coupling system. They are fixed in place by radial set screws, equally distributed along the perimeter to enable rotation of each module in steps of 90 degrees. These modules are machined from polyacetel copolymer, a very strong technical plastic that is readily available of the shelf and easily machinable. With a density of only 1410kg/m^3, it is a great weight saving replacement for aluminum. Our basic modules are divided in three different classes: pressure housings, flooded extensions and end sections.

For the development of DART, the main pressure housing is based on a 80cm long glass cylinder with two hemispherical end caps. The cylinder has an outer diameter of 187mm and an inner diameter of 159mm. The whole housing is rated to 5000 meters, and it was ordered from Nautilus GmbH, a German company specialized in glass deep-sea housings. The weight of the hemispherical end caps is approximately the same as their half-sphere buoyancy, but the dimensions of the glass tube yield approximately 1kg of buoyancy for each 10cm of length. This means that the overall housing provides about 8kg of buoyancy, which is extremely important to compensate the weight of batteries and onboard electronic systems.

The end caps were ordered with bore holes for right angle bulkheads. Each end cap has 8 of these bulkheads, with one vacuum port in the center of one of them (fig. 3) to test for sealing and to dry the interior air. With this configuration, all external cabling is routed within the flooded extension sections, minimizing drag and the risk of entanglement.

To facilitate the installation of onboard electronic systems, 3 small guiding profiles were glued to the inner part of the glass tube. This was done with a flexible bonding compound to mitigate the risk of fracture in high pressures. The guiding profiles serve to position a matching lightweight structure assembled from 10mm aluminum profiles. This structure locks in a specific position to avoid motion during operations. When the cylinder is closed, it is important to insert dry bags of silica gel to absorb any internal humidity and avoid condensation in deep, cold waters.

The whole cylinder was mounted inside a polycarbonate tube with 200mm of external diameter and 3mm of wall, to provide mechanical protection and mechanical terminations compatible with the other modular sections. The wet extensions are flooded sections used to install external sensors and use the same design as with MARES. They propagate the male/female coupling system, therefore they can be easily swapped and installed in different configurations.

The configuration of the propulsion system is also similar to the succesful configuration of the MARES AUV, with two rear thrusters providing surge and differential heading control, while two independently controlled through-hull vertical thrusters manage heave and pitch angle. At the time, all thrusters are oil filled brushless thrusters from Seabotix, but in the future we plan to test also with different brushless versions from Bluerobotics. This thruster configuration is particularly interesting in deep water applications, not only because of the implicit hovering capability but also because it enables the vehicle to keep in a vertical pose thus guaranteeing fast descents and ascents as demonstrated with the MARES AUV in [13]. Additionally, the capability to dynamically compensate for changes in weight and/or buoyancy is desired for this AUV, for example to accommodate the release of a drop weight.

In order to compensate the weight in water and achieve a slightly buoyant vehicle (for safety reasons), some of the inner parts of the flooded sections were filled with syntactic foam. In the case of DART, we have designed and machined parts from LD2000 blocks, a buoyancy material from BMTI, France, with a density of 420kg/m^3.

B. On Board Electronics

The onboard electronic systems are mounted in a lightweight frame that slides into the glass tube (fig. 4). The energy to all vehicle subsystems is supplied by a pack of 8 Li-Ion rechargeable batteries that provide about 800Wh of energy, enough for over 15 hours of operation at 1m/s. A set of battery management boards monitors the status of the batteries and converts the nominal 14.4V battery voltage into the other voltage levels required on board. As a safety measure, the internal temperature of the cylinder is also monitored and logged.

The onboard processing is done by a single board computer (SBC) that is physically installed in a OEM motherboard. In order to save internal space and reduce wiring, the same motherboard also serves as an interface with peripherals and

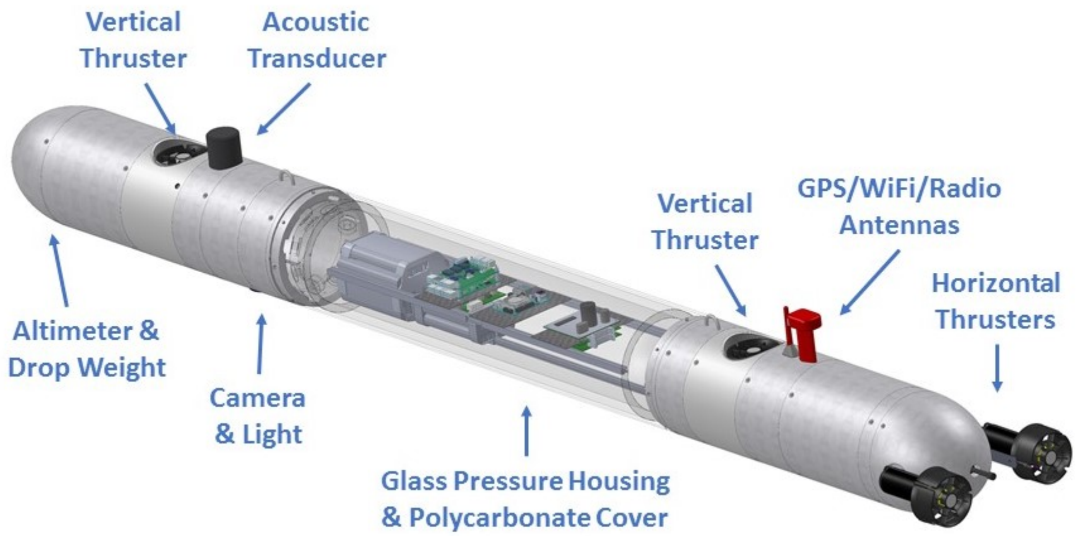

Fig. 2. Schematic overview of the main DART subsystems.

Fig. 3. DART pressure housing end caps, with right angle bulkheads installed in glass hemispheres. The bow end cap in the right-hand side has a vent port in the center.

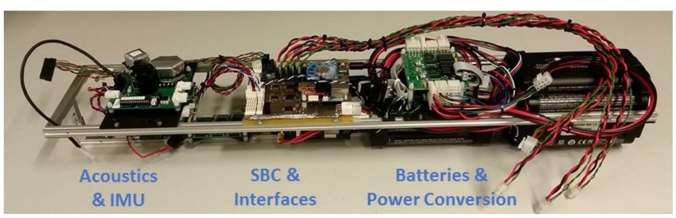

Fig. 4. Distribution of electronics in the internal frame that slides inside the glass tube.

Fig. 5. Frame with onboard electronics installed inside the pressure housing.

power distribution. The power lines can be switched off to save power for external devices in long range missions.

In the first version of DART, the SBC is an Odroid XU4, an octacore ARM working at a maximum of 2GHz, that can run many versions of Linux. The main reason for choosing this SBC was the ability to control electrical power by changing the clock frequency and the number of running cores, but any other Linux running SBC may be used with minimal implications. Using a SBC that runs a standard Linux distribution means that our existing software modules can be seamlessly integrated.

The interface board connects to the low power SBC trough a USB port, providing a total of 16 serial ports for sensors and actuators. The board provides 4 TTL level ports, 8 RS-232 ports and 4 RS-485 ports. For each port there is an associated power connection that supplies regulated +5V, +12V, and -5V, as well as raw battery power and GND. The on board DC/DC converters can supply up to 15A at +5V and +12V and 400mA at -5V. The vehicle thrusters are connected to a dedicated power bus that is fed by a dedicated high power DC/DC converter. The thrusters are also connected to a specific RS-485 port that already provides connection for multiple nodes.

All mission data and sensor logs are stored in solid state memory. The SBC interfaces with external sensors and actuators via the bulkheads installed in both end caps (fig. 5).

C. Navigation and Control

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. The depth of the vehicle can be estimated using a pressure sensor, and DART has a piezoresistive pressure transmitter from Keller AG. Since the error is a percentage of the full scale (0.05% in this case), we have installed a 200bar version in the first version of DART.

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 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. This can be 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.

DART includes a set of OEM acoustic boards that can be used to measure distances to acoustic beacons by counting travel times of acoustic signals. These boards have been used in multiple operations and ensure absolute errors of a few decimeters [14]. To save power in long range missions, the vehicle can use the One-Way Travel Time technique, which requires the synchronization of the onboard clock to the one on the beacons. This can be done using the PPS signal from GPS, at the surface, and then use the Firefly GPS receiver installed onboard to keep accurate timing when the vehicle dives. When the beacons are at the surface, the acoustic transducer is placed looking up, such as depicted in figure 2. In the case of bottom moored beacons, then the transducer section can easily be rotated so that the transducer faces down.

Even with the fastest possible transmission of acoustic signals, the best update rate on range measurements can barely exceed one per second. The navigation system of DART integrates these ranges with thruster RPMs, and data from a XSense MTi IMU, using an extended Kalman Filter. DART has also a Tritech altimeter that can be used to navigate at a given height above the seafloor.

In terms of motion control, DART uses the same set of maneuvers and controllers as developed for the MARES AUV, and described in [13] and [15]. These controllers have been tuned for many different versions of the MARES AUV, and the same procedure needs to be done for DART, to account for any new subsystem that affects the parameters of the vehicle hydrodynamic model (e.g. mass, moment of inertia, center of mass, etc.). In the case of deep water operations, the controller described in [13] is particularly relevant, since it ensures that the vehicle dives to a predefined depth with a vertical attitude, minimizing horizontal motion.

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.

D. Payload Sensors

The initial version of DART was configured for seafloor surveys, taking advantage of the hovering ability to navigate at slow speeds close to the bottom. This is ensured by an underwater camera (a Mako IP camera installed in an aluminum pressure housing) and illumination installed on the bow. Navigation close to the bottom is ensured with data from the down-looking altimeter. Given the modular architecture, other sensors can easily be installed in specially designed sections.

E. Additional Features

For deep water operations, descending time (and energy) can be significant. For this reason, we have developed a new nose cone that incorporates a drop weight that ensures a fast descent with minimum power (2W to hold 1kg). The drop weight assembly is composed by an electromagnet, a weight and the altimeter that are mounted on a rotating platform fitted inside the vehicle's nose. When the vehicle is deployed, the weight is held in place by the electromagnet and the rotation platform allows for the assembly to become vertically aligned. This allows the vehicle to measure its vertical distance to the bottom with the altimeter. By the time the vehicle reaches the desired depth the electromagnet is powered off and the weight released. As the vehicle returns to its natural, horizontal attitude, the rotating platform follows that motion, locking on its final position with the help of a magnetic coupling, and the vehicle proceeds with the planned survey.

V. Vehicle Launch

DART is a case of a portable AUV and even with extra payload sensors, it is not expected that it exceeds the range of 50–60kg. This means that it can easily be launched and recovered from a RHIB by two operators. However, for automated deployment of the AUV, and later recovery from the surface, a special launch and recovery system (LARS) has been designed.

The LARS system is composed of a moving aluminum and stainless steel structure activated by 12V linear actuators. In a

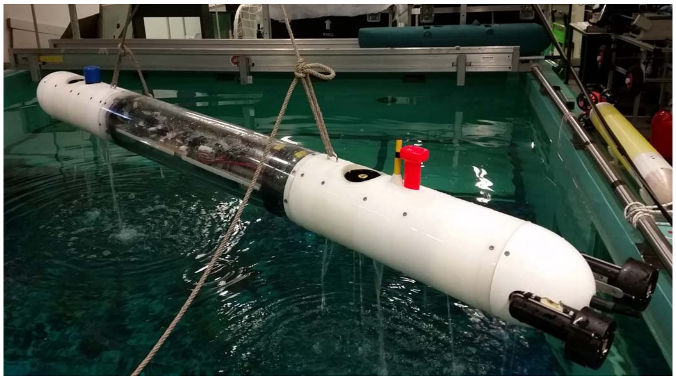

Fig. 7. DART being tested at INESC TEC facilities.

retracted position the LARS seats completely horizontal (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.

VI. Conclusion and Future Work

This paper describes the development of DART (*Deep water Autonomous Robotic Traveler*), a portable, modular, hovering AUV for deep water operations. This vehicle has been designed taking advantage of a modular architecture for underwater vehicles, that has been developed for more than 10 years. Our AUV building blocks includes both physical parts and also software and control systems. These modules can be rearranged, replaced or individually redesigned to yield a great variety of AUV configurations in a relatively short time. For the development of DART, the main pressure housing has been designed as a glass tube with hemispherical end caps, ensuring a depth rating of 5000 meters. The full design includes the interface with the other mechanical blocks available for multiple sensors and actuators. To our knowledge, DART is the first man-portable hovering AUV for deep waters, and a truly modular vehicle.

The first version of the vehicle has been assembled and has gone through the first tests in water tanks. These include buoyancy adjustments, trimming for pitch and roll, and parameter estimation to tune the motion controllers (fig. 7).

As for the immediate future, the operational tests will proceed to open waters, with simple missions in increasing water depths. The integrated navigation and control system has also to be validated in deep waters, ensuring that the vehicle can accurately estimate its position, but also that the operator may track the location of the AUV in real time. At the same time, payload sensors will be integrated to prepare the vehicle for science missions. These will include a series of operations in deep water scenarios close to shore, taking advantage of the reduced logistics required for the operation of DART.

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