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Design of a modular Autonomous Underwater Vehicle for archaeological investigations

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***Abstract* — MARTA (MARine Tool for Archaeology) is a modular AUV (Autonomous Underwater Vehicle) designed and developed by the University of Florence in the framework of the ARROWS (ARchaeological RObot systems for the World's Seas) FP7 European project. The ARROWS project challenge is to provide the underwater archaeologists with technological tools for cost affordable campaigns: i.e. ARROWS adapts and develops low cost AUV technologies to significantly reduce the cost of archaeological operations, covering the full extent of an archaeological campaign (underwater mapping, diagnosis and cleaning tasks). The tools and methodologies developed within ARROWS comply with the "Annex" of the 2001 UNESCO Convention for the protection of Underwater Cultural Heritage (UCH). The system effectiveness and MARTA performance will be demonstrated in two scenarios, different as regards the environment and the historical context, the Mediterranean Sea (Egadi Islands) and the Baltic Sea.**

Keywords* — *Autonomous Underwater Vehicles, Marine Robotics, Underwater Robotics, Underwater Cultural Heritage.

I. Introduction

A team of new heterogeneous AUVs has been developed in the framework of the ARROWS FP7 European project (www.arrowsproject.eu). In this work, the authors focus their attention to the criteria adopted for the design of a modular AUV (Autonomous Underwater Vehicle), namely MARTA (MARine Tool for Archaeology).

MARTA vehicle is composed of several modules, each one dedicated to a particular task (e.g. propulsion, sensor payloads, power supply, etc.). This way, MARTA AUV can be easily customized according to the archaeological mission profile to perform. MARTA prototype is deployable from a small boat; the vehicle is modular and has a total length of about 3.5 m (depending on its configuration), an external diameter of 7 inches and an in-air weight of about 80 kg. The vehicle has 5 degrees of freedom fully controllable by means of 6 actuators (electrical motors + propellers): 2 rear propellers, 2 lateral thrusters and 2 vertical thrusters. The propulsion system is redundant: the vehicle is equipped not only with thrusters. The vertical translation and the pitch configuration can be controlled also through two buoyancy modules (placed one in the bow and one in the stern); this way, the vehicle can be controlled even near the seabed, without exploiting the propellers and thus avoiding moving and spreading sand or mood that can create issues for the acquisition of optical and acoustic data. In Fig. 1, the final 3D CAD of MARTA AUV is given.

Fig. 1. Final CAD design of MARTA modular AUV

II. MAIN VEHICLE CHARACTERISTICS AND PROPULSION SYSTEM

To summarize, the main vehicle characteristics are:

- Reachable depth: 150 m;

- Vehicle maximum (longitudinal) speed: 4 knots;

- Autonomy: about 4 hours;

- Weight: about 80 kg;

- Modularity: the archaeologists involved in ARROWS look for specialized vehicles, i.e. suitable AUVs with specific sensors for specific missions. MARTA is thus configurable, thanks to its different modules, according to the underwater mission profile to perform;

- Hovering capability: the vehicle, either on surface or underwater, is able to perform hovering. It has 5 degrees of freedom (DOFs), not roll, fully controllable.

MARTA's modules, manufactured by TWI Ltd and STERN Progetti s.r.l. (Italy), are in Al Anticorodal and house the following components: 2 buoyancy modules developed by AMT, 2 main vital computers ODROID-XU, 2 different acoustic modems, 1 depth sensor by SensorTechnics, 1 Inertial Measurement Unit (IMU) Xsens MTi-G-700 GPS and 1 Single-axis Fiber Optic Gyro (FOG) DSP-1760 by KVH, 1 Doppler Velocity Log (DVL) NavQuest 600 Micro, 1 Radio modem by RF SOLUTIONS, 6 22.2V LiPo batteries by MaxAmps, a magnetic activation switch, and the acoustic and optical payload devices. More details about the modules are given in the dedicated section.

MARTA modularity is ensured also from an electrical point of view. The electrical interfaces of each MARTA module are standard on both the sides in order to permit each module to occupy the desired position within the whole vehicle and to be added or removed according to the necessity of each mission. In particular, at each interface, two power supply cables (GND and +22.2V) are present with a standard connector that prevents potential polarity inversion. Data exchange through the several modules is ensured by means of an Ethernet cable present at each interface. Finally, the CAN bus connectors are present ensuring the possibility of controlling the actuators of each module through the bow or the stern PC.

As regards the vehicle actuation, as visible in Fig. 2, the default propulsion layout of MARTA AUV is composed of six motors with fixed pitch propellers [6],[7] (two main propellers on the vehicle stern, two lateral thrusters and two vertical ones) used to control all the degrees of freedom of the vehicle, except the roll one. This propulsion layout is quite similar to other existing torpedo-shaped vehicles, e.g. the Folaga AUV produced by Graaltech [4]. A brushless motor coupled with a fixed pitch propeller through an epicycloidal gearbox controls each thruster.

In order to seal the motor, to compensate the external pressure and to protect the electrical and mechanical components from corrosion and excessive overheating, both motor and gearbox are filled with an inert liquid, typically a lubricant oil or a halogenated hydrocarbon with known stable properties [5]. Compared to previous projects [1],[1],[3],[8] a sensorless drive system is adopted.

As concerns the payload, MARTA is capable of housing specific devices for the archaeological mission, e.g.:

- Acoustic payload: a 2D forward-looking sonar Teledyne BlueView M900 is mounted in the bow of MARTA;

- Optical payload: a dedicated MARTA's module houses the optical payload devices (a couple of Basler Ace cameras for stereo vision, a C-laser Fan from Ocean Tools, four LED illuminators produced by the Mechatronics and Dynamic Modelling Laboratory (MDM Lab) of the University of Florence, and a SBC Commell LS-378 for data acquisition and processing).

III. ARROWS TEAM OF VEHICLES: GENERAL ARCHITECTURE

ARROWS project proposes a team of heterogeneous autonomous underwater vehicles capable of satisfying the needs of a complete archaeological campaign. The differences among the AUVs involved in ARROWS are related to the different roles that have to be covered within the cooperating team. In particular, three main roles are identified:

- *Search AUV*: AUV equipped with acoustic sensors such as Side-Scan Sonar (SSS) or Multibeam Echo Sounder (MBES) to be used for fast and large surveys, searching for points of interests (candidate points);

- *Inspection AUV*: the role of the inspection AUV is to reach the points, identified as potentially interesting thanks to the data acquired by the Search AUV, and to acquire optical and/or acoustic images in order to confirm or not the candidate points and to obtain more details;

- *Biomimetic Robot (BR)*: its main role is the wreck penetration to get images from hardly accessible areas; the main features of BRs are small sizes and high manoeuvrability in addition to low cost, considering the not negligible risk of loss.

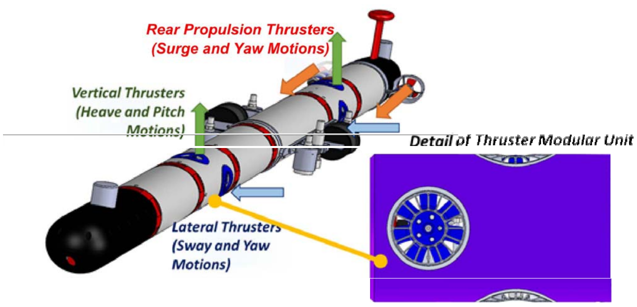

Fig. 2. MARTA AUV, division in modules and propulsion system

All the vehicles cooperate thanks to the distributed High-Level Control System (under development at the Heriot-Watt University, Scotland) that exploits a distributed world model built on board each vehicle through the acquired knowledge and information received by the other vehicles. This way, by exchanging only few synthetic information (to not saturate the communication band), the AUVs will be able to conduct a common mission with a common goal. Because of their simplicity and because the target environment (inside shipwrecks) is not the same of the AUVs (outside the wrecks), the world model will not be implemented on the BRs (U-CAT, a biomimetic robot developed by the Tallinn University of Technology, Estonia); this allows also a reduction of the required performance and, thus, of costs, for their on board PC.

According to the ARROWS Archaeological Advisory Group (AAG) requirements, one of the main design criteria for MARTA is the modularity. Depending on the mission to perform, MARTA is designed to be configured with several payloads and also different propulsion systems. This way, MARTA can play both the role of search and inspection AUV.

As concerns the underwater communication means, MARTA is equipped with two different acoustic modems:

- Evologics 18/34: it will be used for the communication between the conventional AUVs of the team, allowing a high data transfer rate (13.9 kbit/s) and a high functioning range (3500 m); it will be used along with an USBL transducer by Evologics for localization and navigation purposes;
- AppliCon SeaModem: it will be used for the communication with the BRs; U-CAT role justifies the use of a different communication means, characterized by a considerably lower cost although with lower performances (data transmission rate and operating distance).

Thanks to this configuration, MARTA will represent a bridge node in the communication between the AUVs and the BRs. An acoustic communication [11] and localization protocol, oriented to the optimization of the exchanging data rate and of the accuracy in sensory data geo-referencing, will be developed, tested and demonstrated during the final experimentation of ARROWS. The protocol will take into account the constraints in terms of acoustic channel sharing among a variable number of different acoustic nodes (Evologics USBL, Evologics modem, AppliCon SeaModem). A TDMA (Time Division Multiple Access) protocol will be the first solution; then an iterative procedure will bring to the definitive version according to the feedback coming from the simulation results and the testing activity outcomes.

Fig. 3. MARTA AUV prototype

IV. MARTA AUV PROTOTYPE

MARTA AUV prototype (Fig. 3) is ready for its first navigation tests at sea.

In this section the description of the first versions of MARTA modules is given. The choice of Al Anticorodal type 6082 T6 is a good trade-off among workability, lightness and mechanical strength. To have high resistance against salt water a hard anodising process is mandatory. The modules are connected together with suitable plastic wires: the assembling and disassembling phases are very simple and fast.

MARTA AUV becomes watertight only after the modules are connecting together (the only wet sections are the final part of the bow and the final part of the stern): two radial O-rings are placed at the end of each module (e.g. see Fig. 5) and assure a watertight connection. It is worth to note that expensive underwater connectors are mandatory only in the interfaces of the bow and the stern. After the whole vehicle assembly, a depressurization of 0.3 bar is created inside by means of a vacuum pump to ensure a better alignment between the modules and to provide an adequate stiffness.

Starting from the bow, in Fig. 4 its wet and watertight sections are shown.

Fig. 4. MARTA bow

In front of the wet part of the bow the 2D forward-looking sonar Teledyne BlueView M900 is placed: it records acoustic 2D images and is used to reconstruct the environment in front of the vehicle. It is connected through an Ethernet cable. The angle of the sonar with respect to the horizontal is adjustable in the range between 10° to 20°. Not reported in the picture, in the wet part of the bow, as well as in the wet part of the stern, there are also a drop-weight and a buoyancy unit (both developed in the framework of the project). In the watertight part the “bow electronics” is placed. Moreover it houses also one of the navigation (vital) computers, ODROID-XU, and the electronic boards of the acoustic modem Evologics 18/34.

Fig. 5. Thruster module

After the bow, there is the first thruster module (Fig. 5). The thruster module houses one lateral and one vertical thruster. As concerns both the main rear propellers and the lateral and vertical thrusters, a “standard” solution consists in making these electrical motors (100 W) watertight, filling in with dielectric-oil and connecting them to suitable marine propellers (e.g. plastic propellers printed with the 3D rapid prototyping machine owned by MDM Lab). Since vertical and lateral thrusters are incorporated in the hull of MARTA AUV, the water flow boosted by the propeller is limited and makes impossible to design a proper nozzle in order to maximize the thrust. In these conditions, e.g. a Ka-4-70 propeller (a very common one) would not be efficient: for this reason it has been designed a customized propeller like the one shown in Fig. 6. To determine the optimal propeller geometry, various shapes have been tested, varying the number of blades and the p/d ratio.

Fig. 6. MARTA thruster propellers

In the cental part of the vehicle, there is the battery module. This is only a simple Al pipe housing three or six (depending on the desired autonomy for a mission) LiPo cells battery packs. Each battery pack is by MaxAmps, LiPo 11000 mAh, 6 cells 22.2 V. A group of three batteries fits well inside the 7’ module hull. It is worth to note that the battery module can be replaced by the vision one; in fact, if the above-mentioned optical payload is needed for a mission the vision module replaces the battery ones since the former has already on board the dedicated LiPo cells for the power supply. This way, overstretching the vehicle is not necessary. Connected to the battery module there is another thruster one (Fig. 5), before MARTA stern.

Fig. 7. MARTA watertight stern

In the watertight part of the stern (Fig. 7) the dedicated “stern electronics” is placed. Moreover it houses also the other navigation (vital) computer, ODROID-XU, the electronics of the acoustic low cost SeaModem by AppliCon and the antenna. The antenna houses a GPS and the communication devices: they are connected to ODROID-XU computer and allow to exchange data with other vehicles and operators:
- WiFi AccessPoint, Ubiquiti PicoStation: it allows a fast, high-band, short-range communication on the surface. It is connected directly through Ethernet cable;
- Radio Modem, Amber Wireless AMB8355-RF Data Modem: used to send short messages from high distances on surface. It uses RS-232 protocol and it is connected through a serial-USB adapter.
As concerns the navigation [9],[10],[12],[13] sensor set, MARTA watertight stern has on board:
- the electronics of the pressure sensor, by SensorTechnics: it is used to estimate the vehicle depth. The communication is made by I2C protocol;
- 1 IMU (Inertial Measurement Unit), Xsens MTi-G-700 GPS: it provides data from 3D internal accelerometer, gyroscope and magnetometer, and also an estimation of the vehicle orientation. It is connected through its own USB cable;
- 1 FOG (Fiber Optic Gyroscope), KVH DSP-1760: a single axis gyroscope with high precision used to improve the pose estimation (in particular the yaw measurement). It uses a RS-422 protocol and is connected through a serial-USB adapter.

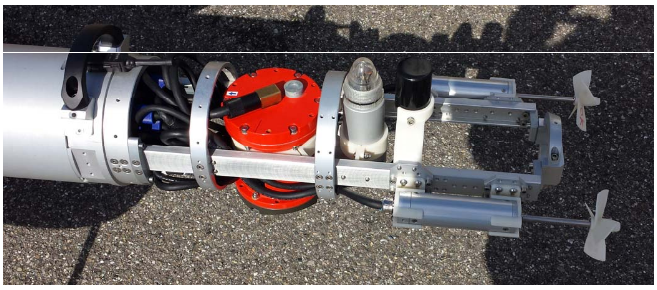

Fig. 8. MARTA wet stern

Finally, MARTA wet stern (Fig. 8) has on board:
- 1 DVL (Doppler Velocity Log), NavQuest 600 Micro: it provides a 3-axial linear speed measure referred to the seabed exploiting the Doppler effect on acoustic waves produced by the sensor itself and reflected by the sea bottom. It uses RS-232 protocol and it is connected through a serial-USB adapter;
- a custom beacon flash developed by MDM Lab that starts emitting intermittently when ambient light falls. It is useful to quickly locate the vehicle when it is on surface or slightly immersed;
- the low cost SeaModem by AppliCon;
- the two main rear propellers.

V. Conclusions

The paper describes the design of MARTA AUV, acronym for MARine Robotic Tool for Archaeology: it is a modular Autonomous Underwater Vehicle (AUV) developed in the framework of the European ARROWS project. The paper summarizes the main characteristics of the vehicle, both concerning its electro-mechanical architecture, the navigation sensor set and its payload capability. The first prototype of MARTA AUV is now ready and its sea trails are scheduled for Spring-Summer 2015 (e.g. during the official ARROWS demo in Sicily at the end of May).

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