The ARROWS project: adapting and developing robotics technologies for underwater archaeology

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Abstract: ARchaeological **RO**bot systems for the **W**orld's **S**eas (ARROWS) EU Project proposes to adapt and develop low-cost Autonomous Underwater Vehicle (AUV) technologies to significantly reduce the cost of archaeological operations, covering the full extent of archaeological campaign. ARROWS methodology is to identify the archaeologists requirements in all phases of the campaign and to propose related technological solutions. Starting from the necessities identified by archaeological project partners in collaboration with the Archaeology Advisory Group, a board composed of European archaeologists from outside ARROWS, the aim is the development of a heterogeneous team of cooperating AUVs capable of comply with a complete archaeological autonomous mission. Three new different AUVs have been designed in the framework of the project according to the archaeologists' indications: MARTA, characterized by a strong hardware modularity for ease of payload and propulsion systems configurationchange; U-CAT, a turtle inspired bio-mimetic robot devoted to shipwreck penetration and A Size AUV, a vehicle of small dimensions and weight easily deployable even by a single person. These three vehicles will cooperate within the project with AUVs already owned by ARROWS partners exploiting a distributed high-level control software based on the World Model Service (WMS), a storage system for the environment knowledge, updated in real-time through online payload data process, in the form of an ontology. The project includes also the development of a cleaning tool for well-known artifacts maintenance operations. The paper presents the current stage of the project that will lead to overall system final demonstrations, during Summer 2015, in two different scenarios, Sicily (Italy) and Baltic Sea (Estonia).

1. INTRODUCTION

In recent years the interest in underwater projects, the development of specific tools dedicated to archaeology and more in particular the use of AUVs are increasing (Bingham et al. (2010)), (Mahon et al. (2011)), (Nuno Gracias. (2013)), (Roman and Mather (2010)). ARROWS [1] (logo in figure 1) is the acronym for ARchaeological RObot systems for the Worlds Seas. The project started in September 2012 and his consortium comprises expertise from underwater archaeology, underwater engineering, robotics, image processing and recognition from academia and industry (10 partners from 5 different countries are involved). The challenge faced by ARROWS is to generate and adapt existing technologies in the field of military, security and offshore oil and gas applications, in order to develop user-friendly and low cost Autonomous Underwater Vehicle (AUV) technologies for archaeological investigation in different sea environments. Two different demonstration sites will be used, one in the Baltic Sea and one in the Egadi archipelago (Sicily). The archaeological requirements and needs, related to the two different scenarios, have been faced and translated into technical specifications by the ARROWS engineers. The paper presents the current stage

Fig. 1. ARROWS project logo

of the project and it is organized as follows. Section 2 exposes the requirements coming from the archaeologists involved in the project; in section 3 a description of the architecture of the high level management system for AUVs integration and cooperation is provided; section 4 describes the main features of the new vehicles designed within the project according to the archaeologists' specifications; in section 5, details about the process thatled to the current version of the cleaning tool, developed within the project, for underwater artifacts maintenance are discussed; section 6 is about payload data processing both of acoustic and optical sources including preliminary results of the project; finally, section 7 summarizes the current stage of the project and explains the future steps towards the final demonstrations.

2. ARCHAEOLOGICAL REQUIREMENTS

Requirements for ARROWS vehicles defined by archaeologists, both project partners and from outside the consortium, are oriented to the satisfaction of archaeological aimed missions, to be performed both in the Mediterranean Sea and in the Baltic Sea. The two sea areas present very different features mainly as concerns physical conditions (temperature, water density, etc.) and environmental characteristics (visibility, turbidity, etc.). This implies requirements of easy adaptability for the ARROWS vehicles;

[1] ARROWS project Website: www.arrowsproject.eu

e.g. the AUV weight and buoyancy can be finely tuned through dedicated devices to maintain an overall neutral condition against local density modifications. In addition both acoustic (e.g. Multi-Beam Echosounder, Side-Scan Sonar) and optical payloads are integrated on the ARROWS vehicles to deal with all the possible visibility conditions and to "see" even in presence of high turbidity. Two demonstration scenarios have been identified in Mediterranean Sea and in the Baltic Sea to validate the system performance under different conditions. On the archaeologists' side the main requirements were concentrated in the problems concerning positioning systems. The archaeologists need to come back to identified targets without difficulties. It means that AUV must have a precise positioning system. AUV has to be equipped with a positioning device that will aid in determining its location and facilitate its retrieval in case of a malfunction or bad weather conditions. Consequently it is necessary to produce precise archaeological underwater maps with a positioning error less than 1 meter. Due to economic problems, typically affecting the archaeological research field, it was discussed the possibility to produce limited size AUVs to be easily handled and guided by less specialized operators and, consequently, reducing to the minimum both vehicles cost and expenses for their operation. Reduced size AUV will entail an overall cost reduction, allowing deployment and recover either from land or from a small boat. The main challenge is to design AUVs for the archaeologists that could compete with the commercial ones either in the field of efficiency, capacity and cost while covering allthe phases of an archaeological mission. According to this necessity, many different functionalities and behaviors are required for the ARROWS AUVs. It has been decided in the design phase to fulfill with this requirement through two ways: on one hand different capabilities have been distributed on different cooperating vehicles, constituting a heterogeneous team composed of already existing vehicles and the three new ones developed from scratches (section 4), in order to maximize the number of possible operations maintaining limited the dimension of each single AUV; on the other hand the design phase followed the principle of the modularity (form the hardware and the software points of view): through this choice a rapid reconfigurability of the AUV capabilities is ensured. One of the required capabilities for the ARROWS system is the shipwreck penetration through AUVs. Studying the interior of the shipwreck has always been extremely challenging, also for experienced divers and even for the best ROVs and their operators. The danger of getting trapped inside the wreck is very serious and may cause the loss of the expensive equipment, or even the human life. To comply with the necessity, in ARROWS Project, the development of a small bio-mimetic AUV is proposed, which should be able to enter the shipwrecks and navigate exploiting dedicated sensors biologically inspired and record video of the ships interior. If this AUV proves to be successful, it would be a very useful addition to the archaeologists "toolbox", which could help with identifying the sunken ships and determining the exact causes of the sinking.

The production of archaeological devoted AUV team will contribute to fulfill the requirements of 2001 UNESCO Convention for the Protection of Underwater Cultural Heritage (ratified by so many countries to be nowadays legally operative). According to such convention it is better that the archaeological objects found on the seabed will be left in their original contexts. This implies that we have to optimize the control and management of underwater cultural heritage without removing any object. But also it requires that we have to understand the contexts and the real nature of archaeological sites without any rescue. It means that our museums will be on the seabed. Of course this can be possible if we reach a high standard of knowledge of such sites. ARROWS researchers gave wide attention to such requirements projecting an AUV use aimed to fulfill what was defined by the above UNESCO convention. Moreover, some classes of well-known sunken artifacts need a periodic cleaning activity; one of the goals of ARROWS project is the production of a device (Cleaning Tool - CT) to be physically attached to one of the involved vehicles even if independent from a power supply and control point of view.

3. HIGH LEVEL CONTROL SYSTEM

An inherent goal of the ARROWS project is to achieve persistent autonomy of an underwater multi-vehicle system (Tsiogkas et al. (2014)). There is one main problem that must be solved in order to achieve this: how to efficiently share information (of the world and mission) between platforms in the marine domain. Thus, our proposed solution is shown in figure 2 where the problem is addressed by the use of a distributed World Model (WM) service (Maurelli et al. (2012)). The WM is stored within an ontology (Bechhofer et al. (2004)), a formal method of representing knowledge about a domain. During a mission, the local WM of each vehicle is synchronized with all other vehicles' WM; only information that the vehicle is pre-programmed to "need" is synchronized in order to optimize information exchange in the low bandwidth acoustic communication channel. The control of what information is to be sent during a vehicle's Time Division Medium Access (TDMA) time-slot is managed, transparently, by the "Exchange Manager" module. Doing this at the information level as opposed to the packet level means there is no requirement to explicitly plan transmission from within the executor.

Using this approach, both knowledge of the world, such as object detections, and mission information, such as tasks to be executed, are shared through the distributed WM. This simplifies the Mission Executive module (currently implemented as a Finite State Machine) and allows adaptive mission planning. For example, on initialization, an inspection vehicle shall ask other vehicles to send it information related to inspection targets; then, during operation, its Mission Executive module checks its local WM for new targets. If there are multiple targets, the Mission Planner is used to plan the order in which the targets are visited. After the plan is created, the vehicle inserts that it is inspecting that target into its ontology; this new information is then shared with other vehicles through the Exchange Manager allowing them to adapt their behaviour is necessary.

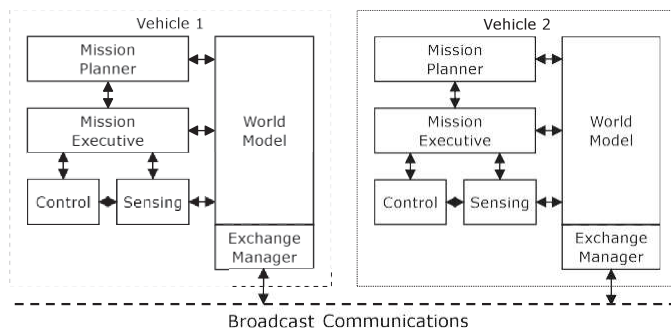A so designed architecture allows a dynamical reconfigura-

Fig. 2. The distributed world model architecture used for the ARROWS project. The exchange manager enables the information sharing among the vehicles in a decoupled manner from the vehicle planning and execution modules.

tion of the mission according to the information achieved by single vehicles through the related payload and shared by means of the TDMA policy with all the other cooperating vehicles as soon as possible.

4. VEHICLES

4.1 MARTA

MARTA (MARine Tool for Archaeology) is a modular AUV designed and developed by the University of Flo- rence. According to the archaeologists' requirements, the modularity is an important feature: thus instead of having different vehicles for different kinds of mission, a single reconfigurable AUV has been developed and can be used by the archaeologists. MARTA AUV can be easily customized according to the mission profile to perform and will be easily deployable from a small boat; the vehicle is modular and has a total length of about 3 m (depending on its configuration), an external diameter of 7 inches and an in-air weight of about 90 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 (Carlton (2007)). The archaeologists asked for a redundant propulsion system: the vehicle is equipped not only with thrusters. The vertical translation and the pitch control can be performed also by means of 2 buoyancy modules (placed one in the bow and one in the stern) designed by AMT; this way, the vehicle could be controlled, e.g. near to 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 (figure 3). To summarize, the main vehicle characteristics are a reachable depth of 150 m, a maximum longitudinal speed equal to 4 knots, an autonomy of about 4 hours, hovering capability (5 DOFs - not roll - actively controllable).

MARTA modules, manufactured by TWI Ltd and STERN Progetti s.r.l. (Italy), are in Al Anticorodal and house the following components: 2 buoyancy control modules developed by AMT, 2 main vital computer ODROID-XU, 2 acoustic modems, 1 depth sensor by SensorTechnics, 1 Inertial Measurement Unit (IMU) Xsens MTi-G-700 GPS, 1 Fiber Optic Gyro (FOG) 1-axis DSP-1750 by KVH, 1 Doppler Velocity Log (DVL) NavQuest 600 Micro, 1 Radio modem by RF SOLUTIONS, 6 LiPo batteries by

Fig. 3. MARTA AUV CAD

MaxAmps, a magnetic activation switch, motor drivers developed by NESNE and the acoustic and optical payload devices. As concerns the payload, MARTA is capable of housing specific devices for the mission, e.g. acoustic payload (a 2D forward-looking sonar Teledyne BlueView M900 can be mounted in the bow of MARTA) or optical payload (a couple of Basler Ace cameras for stereo vision, a C-laser Fan from Ocean Tools and four illuminators produced by the University of Florence). The first sea trials of the vehicle are scheduled for next Spring (2015).

4.2 A_Size AUV

The A Size AUV (figure 4) presents innovative aspects in addressing underwater operations with a fully integrated and modular approach to optimize volumes and weights distribution in the vehicles therefore making easy to interface and host major AUV payloads. This is obtained by scaling down current size of vehicles and all its components and by distributing on various platforms sensors normally contained in a single vehicle, such as optical, acoustic and magnetic are distributed across multiple units increasing their redundancy. Thanks to algorithms that allow the scheduling of different tasks on different platforms managed in real-time by an integrated control software, the vehicles are intended to carry out a cooperative work. Miniaturization effort carried out during this vehicle design brought to the need to develop down scaled components of suitable size to be hosted on board. To

Fig. 4. A_Size AUV

preserve high maneuverability, directional propellers were adopted as opposed to active vanes. The main propulsion is obtained through a brushless motor fitted with magnetic coupling. For what pertains payload a high modularity is implemented. As a standard approach all payloads are communicating with scientific computer via Ethernet. Also from the mechanical point of view, a simple connection of the payload modules have been designed and adopted as a standard.

4.3 U-CAT

U-CAT (Salumäe et al. (2014)) is a highly experimental bio-mimetic AUV, developed to study robotic technologies for assisting archaeologists during shipwreck exploration missions. U-CAT's ultimate goal is to penetrate shipwreck and autonomously collect data from the enclosed areas of the wreck, which are dangerous for divers and inaccessible by tethered vehicles. U-CAT is a low-cost solution that does not incorporate any expensive sensors like DVL, Imaging sonars etc., usually seen on traditional AUVs. Therefore, the cost of the robot is acceptable for studying high-risk scenarios with a considerable chance of losing the vehicle. We realize that fully autonomous navigation of an AUV inside shipwreck is far beyond the state of the art, especially when using only low cost sensing solutions. Therefore, we are concentrating on scenarios that are relatively simple, but can still offer huge benefits for inspecting the wrecks. For example a diver can guide the U-CAT into a dangerous confined area of a wreck (i.e. under the structures in danger of collapse, to cabins through narrow passages etc.). The U-CAT will navigate the room and return to the pinger carried by the diver. With such a feasible mission a lot of useful information can be gathered from inaccessible places without putting the diver in danger. By testing the vehicle in these simple scenarios we will identify the technologies which have the highest potential for being used in more complex missions like internal shipwreck mapping. U-CAT weighs 17 kg and can be operated by a single person. For propulsion U-CAT uses a novel configuration of 4 oscillating flippers to achieve high maneuverability (figure 5). The fins are

Fig. 5. The biomimetic AUV U-CAT

placed so that the robot has holonomic capabilities and control over all the 6 degrees of freedom. The advantages of using flippers instead of propellers inside the wreck are: more quiet locomotion in terms of sediment disturbance; smaller risk of getting tangled; fewer actuators required; higher safety for divers and archaeological site. The main disadvantage of fin locomotion is the difficulty to achieve steady motion required for sensors. We are trying to overcome this issue by developing control approaches that limit the oscillations of the vehicle to a single degree of freedom. We also plan to actively stabilize the camera on this degree of freedom. When the robot is moving at slow velocities, as it usually is during inspection mission, we assume these methods are enough to acquire usable data. In addition to the flippers the robot is equipped with 2 buoyancy control units developed by the ARROWS project partner

Albatros Marine Technologies. The buoyancy control units change the volume of the vehicle by moving 2 pistons, one on the each end of the robot. For navigation the U- CAT carries a pinger localization system that allows itto find homing beacons mounted outside the wreck by diver. It also has 8 custom-developed echosounders for obstacle detection and avoidance. Other included devicesare IMU, depth sensor, Applicon acoustic modem, camera and illuminators. The robot is controlled by a computer with 1 GHz Quad-Core ARM cortex A9 processor. Its60 W brushless DC motors are driven by motor drivers custom-developed by ARROWS project partner NESNE Electronics. The robot has 540 Wh battery that allows at least 4 hours of autonomous operation. U-CAT is designed to dive to maximum depth of 100 m.

5. CLEANING TOOL

One of the critical underwater missions of the ARROWS project is to clean the mud and sand on the underwater archaeological artifacts. This is required to get a clear image of the artifact without the need of excavation. The specifications of the cleaning tool (CT) to be designed are: to operate at 100 m depth; to be mountable on the AUVs; to be run in ROV (Remotely Operated Vehicle) mode; to be able to create water jets to dissolve the mud or dirt on the archaeological object and to suck the dissolved mud or dirt, to have a size to be compliant with theAUVs. The CT will be used by the vehicles (e.g. MARTA or the A Size AUV) in ROV mode: i.e. the CT will be mounted as an external payload with its own power supply to simplify its management. A dedicated camera will help in the monitoring of the cleaning operations.

CT design is carried out based on the Venturi effect principle (figure 6) which allows using a single pump for both producing water jets and suction effect. The principle used in the water ejector part is shown in the figure below. As a result of red flow lines a low pressure volume is created which results in a vacuum effect to suck the dissolved mud or sand. This way no foreign object goes through the propellers of the pump. Based on the above ejector design,
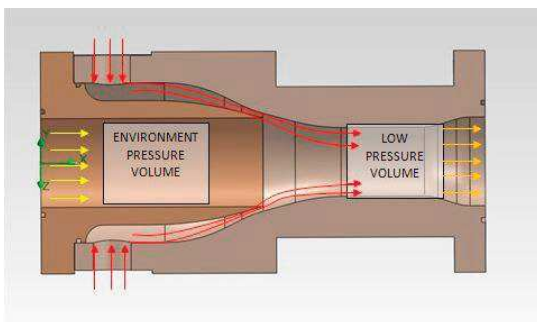

Fig. 6. Cleaning Tool Section

the final prototype (figure 7) of the CT is constructed and tested. The figure below shows the final design. There is a volute on the pump and the ejector to regulate the pressure and have a uniform flow through the ejector inlet. This design is experimentally tested for the suction performance and the forces induced to the AUVs.
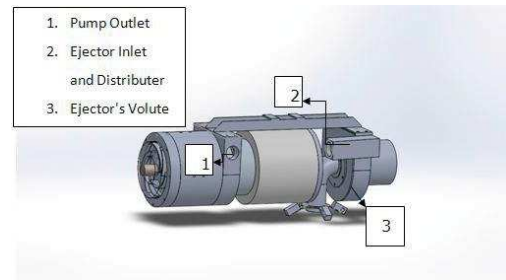

1. Pump Outlet
2. Ejector Inlet and Distributer
3. Ejector's Volute

Fig. 7. Cleaning Tool Assembly

6. PAYLOAD DATA PROCESS

As previously stated the sensors that will collect payload data during the AUVs missions will consist of underwater cameras and side scan sonar or multi-beam echo-sounders. The on-board vision system for optical data acquisition and on-line processing was developed according to a client-server strategy. The main module acquires and stores the images on a shared buffer, which can be accessed asynchronously by the other on-line modules, so that each module can operate at its maximum speed. Other on-line modules include the Simultaneous Localization and Mapping (SLAM) module, providing the AUV position together with a sparse real-time 3D map of the environment, and a machine learning classifier of the seafloor to get an early analysis of scenario explored by the AUV. Off-line versions of both these modules exist to provide more refined results, integrated with mosaic tools for a handy and effective global overview of the explored scenario. Figure 8 shows the photo mosaic obtained by processing the images acquired by the MARTA optical payload system, integrated on University of Florence Typhoon AUV, in Caesarea (Israel) during an archaeological mission funded by the Office of Naval Research Global (ONRG) of the US Navy under the supervision of the Israel Antiquities Authority (IAA). The optical and acoustic maps collected
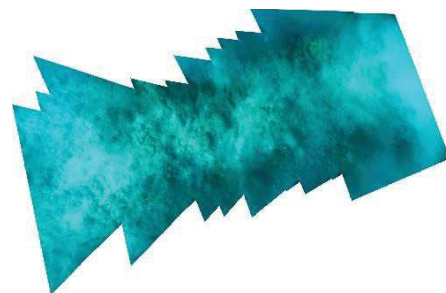

Fig. 8. Photo mosaic of the seabottom in front of Caesarea (Israel)

by the AUVs during the surveys must be processed to understand the environment and to detect targets of interest located on the seabed. Figure 9 shows an acoustic mosaic of a sea area in front of Caesarea exploiting acoustic images acquired through the forward looking multibeam echosounder (MBES) to be integrated on MARTA.

A suitable scene understanding process has to be focused mainly on manmade object recognition and on the identification of the regularity content in the data. This can be pursued by exploiting computer vision algorithms that perform i) the recognition of geometrical curves, ii) the
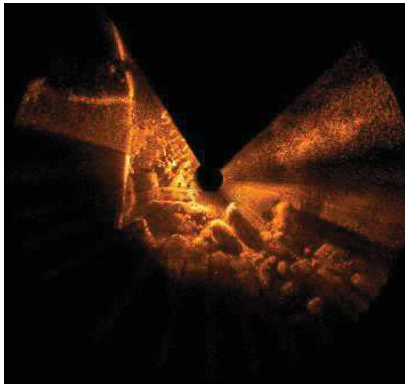
Fig. 9. Acoustic mosaic of the sea bottom in front of Caesarea (Israel)

classification of seafloor areas by means of texture analysis and iii) an integration of multi modal information, aiming at a robust object recognition. The detection of geometrical features in the map represents a clue suggesting the presence of manmade structures. A curve detector has been developed following a statistical approach, to provide the system with reliability and computational performance all at once. As a descriptor of the surface appearance of objects, texture can be employed to classify the surveyed seafloors into categories (sand, rock, vegetation) and to detect anomalies that can be related to interesting objects. By considering the dominant spatial frequency as a signature of texture, the captured data can be clustered and classified (further details can be found in Bertini et al. (2014)). Each sensor provides an individual description of the environment so it can be interesting to conceive a synthesis structure, represented as an N-dimensional map made of several layers. A point in that map refers to the full information available for the corresponding point in the world. It is expected that the extension from the individual sensor analysis to an overall representation of the scenario provides an increase in the object recognition robustness. The captured data together with the data analysis results will be employed for the 3D reconstruction and modelling of the archaeological site and its content. The reconstructed meshes will be refined and integrated in a virtual environment based on a game engine (Unity), and will be programmed to enable user interaction by means of dedicated devices (Oculus Rift and Kinect). This will represent a powerful tool for expert users and for the dissemination of the acquired knowledge to the general public.

7. CONCLUSION

The paper describes the current status of the ARROWS (ARchaeological RObot systems for the Worlds Seas) European project. According to the project time-line, the current year (2015) will be devoted to the testing at sea of the developed Autonomous Underwater Vehicle (AUV) technologies for archaeology. In particular, the tests will start evaluating the performances of the single AUVs before the final demos where the whole system, the heterogeneous fleet, will be deployed at sea for a collaborative mission. To summarize: a short overview of the whole project main aims has been given in the paper. More results about ARROWS project, e.g. concerning underwater naviga-

tion and communication, vehicle cooperation, CT performances and the final results of the archaeological-oriented demos, will be published soon by the authors.

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