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The ARROWS Project: robotic technologies for underwater archaeology

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Abstract. The paper summarizes the main results achieved during the three-year European FP7 ARROWS project (ARchaeological RObot systems for the Worlds Seas). ARROWS concluded at the end of August 2015 and proposed to adapt and develop low-cost Autonomous Underwater Vehicle (AUV) technologies to reduce the operational cost of typical underwater archaeological campaigns. The methodology used by ARROWS researchers identified archaeologists requirements for all the phases of a campaign. These were based on guidelines issued by the project Archaeology Advisory Group (AAG), which comprised of many European archaeologists belonging to the consortium. One of the main goals of the ARROWS project was the development of a heterogeneous team of cooperating AUVs; these comprised of prototypes developed in the project and commercially available vehicles. Three different AUVs have been built and tested at sea: MARTA, characterized by flexible hardware modularity for easy adaption of payload and propulsion systems, U-CAT, a turtle inspired bio-mimetic robot devoted to shipwreck penetration and A-Size AUV, a small light weight vehicle which is easily deployable by a single person. The project also included the development of a cleaning tool for well-known artefacts and maintenance operations. Results from the official final demonstrations of the project, held in Sicily and in Estonia during Summer 2015, are presented in the paper as an experimental proof of the validity of the developed robotic tools.

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1. Introduction

The interest in the underwater field development of specific tools for the sub-sea inspection and in particular the use of Autonomous Underwater Vehicles (AUVs) is increasing [1] [2] [3] [4] [5]. ARROWS project, acronym for ARchaeological RObot systems for the Worlds Seas (http://www.arrowsproject.eu), started in September 2012 and concluded in August 2015. Its consortium comprised expertise from underwater archaeology, underwater engineering, robotics, image processing and recognition from academia and industry. The challenge faced by ARROWS was to generate innovative solutions and to adapt existing technologies from the fields of military, security and offshore oil and gas applications, in order to develop several user friendly and low cost robotic technologies for underwater archaeological investigation. The underwater archaeology field as well as other research fields e.g. biology or geology are not able to exploit traditional AUV technologies because of prohibitive costs. The methodology that led the ARROWS researchers was to identify the archaeologists requirements in all the phases of a campaign, based on the guidelines issued by the project Archaeology Advisory Group (AAG), composed of many European archaeologists belonging to the consortium and not. The archaeological requirements and needs have been translated into technical specifications by the ARROWS engineers. The results related to the first half of the project are given in [6]. In the second half of ARROWS, the final demonstrations were performed both in the Mediterranean and Baltic Seas. Both acoustic sensors (e.g. forward-looking sonar, Side-Scan-Sonar) and optical cameras are integrated on the vehicles to deal with all the possible visibility conditions and to “see” even in the presence of high turbidity. As concerns the main requirements, the archaeologists expect the AUVs to return to identified targets with a high level of positioning accuracy, in order to produce precise archaeological underwater maps. Moreover, the option to produce smaller size AUVs which can be easily handled and guided by less specialized operators which, consequently, reduces operational and logistics expenses. The reduced size decreases costs, but also allows deployment and recovery from a small boat. In the design phase, to fulfill the requirements, two main decisions were taken: balancing different capabilities between distributed cooperating vehicles, constituting a heterogeneous team composed of pre-existing (commercial) vehicles and three new prototypes developed from scratch, in order to maximize the number of possible configurations; the other design phase considered the modularity of the hardware and software. This allowed for a rapid reconfiguration of the AUVs capabilities. Another of the required capabilities for the ARROWS system was for shipwreck penetration. The danger of being trapped inside the wreck is very serious and may cause the loss of expensive equipment, or even human life. To comply with the requirements, the development of a small biomimetic turtle-shape AUV was proposed.
ARROWS outcomes also fulfill the requirements of 2001 UNESCO Convention for the Protection of Underwater Cultural Heritage. According to such convention the archaeological objects found on the seabed will be left in their original context. Moreover, some classes of well-known sunken artefacts require periodic cleaning; in the framework of the project a cleaning device (Cleaning Tool), was developed and successfully tested as a standalone item [7]. The paper summarizes the main ARROWS results achieved at sea with the vehicles.

2. Developed Robotic Vehicles

In this paragraph a brief description of the vehicles developed within ARROWS to satisfy the identified archaeological requirements is given.

2.1. MARTA

MARTA AUV is one of the main outcomes of the ARROWS project. It is an AUV prototype developed and built from scratch. MARTA final version is shown in Figure 1 where the vehicle is navigating on surface of the Baltic Sea. It is composed of many modules, each one

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Figure 1. MARTA AUV in autonomous navigation during ARROWS experiments (Estonia, July 2015)

Figure 2. A-Size AUV in autonomous navigation during ARROWS experiments (Sicily, June 2015)

dedicated to a particular task (e.g. propulsion, sensor payloads, power supply, etc.). Due to its modularity and reconfiguration capability, MARTA AUV can be easily customized according to the archaeological mission to be performed. The vehicle is deployable from a small boat, has a total length of 3.7 m (in its longest and complete configuration), an external diameter of 180 mm and an in-air weight of 80 kg. Its maximum reachable depth is 120 m and the maximum speed 3 kn relates to an autonomy of about 4 hours. The typical cruise speed is 1 kn. MARTA, either on the surface or underwater, is able to perform hovering: it has 5 degrees of freedom (DOFs) fully controllable by means of 6 actuators (electric motors + propellers): 2 rear propellers, 2 lateral thrusters and 2 vertical thrusters. MARTA AUV becomes watertight only after the modules are connected together (the only wet sections are the final part of the bow and the final part of the stern). After the whole vehicle is assembled, a depressurization of 0.3 bar is created inside by means of a vacuum pump to reach a good alignment among the modules and to provide an adequate stiffness. MARTA can house both acoustic and optical payload.

2.2. A-Size

In the wide spectrum of underwater activities, suitable applications for A-Size vehicles (120 mm diameter) in the Underwater Cultural Heritage have been identified. Innovative aspects address underwater operations with a fully integrated and modular approach to optimize volume and weight distribution in the vehicles therefore making it easy to interface and host major AUV payloads. The 120 mm diameter solution called A-Size (Figure 2) corresponds to a vessel length of 1300 mm. A lightweight construction of the hull must be observed: carbon fibre was selected for its specific high Poisson modulus to withstand hydrostatic compression thus

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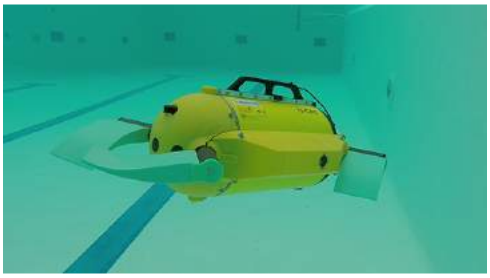

Figure 3. U-CAT biomimetic 4-fin AUV

preserving lightness. The vehicle has a 300 Wh battery, with an endurance of 4 hours in transit navigation. To preserve maneuverability, directional propellers (bow/stern thrusters) were adopted as opposed to active vanes. Main propulsion is obtained through a brushless motor fitted with magnetic coupling. Propeller design variables were fixed after practical and experimental tests. The A-Size vehicle uses an ARM9 based micro-controller board, with Linux configured for embedded applications. While the vehicle is on the surface it may be connected through an optical fibre and communicate with a GPS receiver through an Ethernet connection or be in contact with the operator through a WiFi hotspot.

2.3. U-CAT

U-CAT is a highly experimental biomimetic AUV for shipwreck penetration (Figure 3). Shipwreck penetration is a difficult task that is not usually undertaken due to the high risk of losing equipment or human life. Divers can easily get lost or stuck in wrecks. Remotely Operated underwater Vehicles (ROVs) cannot enter wrecks because of tangling their tethers and current AUVs are mostly not designed for maneuvering and navigating in confined spaces. U-CAT is an AUV/ROV which attempts to fill the gap by providing a low cost tool for gathering video footage from inside shipwrecks. U-CAT is not meant to navigate in complex corridors of shipwreck, but it is designed to be used in relatively simple scenarios, which can still often offer large amounts of useful information. For example autonomous inspection of a single room in danger of collapse. Instead of propellers U-CAT uses 4 pitching fins for locomotion. Such biomimetic design has several advantages which help to meet the archaeologists requirements. One of the main advantages is the versatile maneuverability in tight spaces. The fins are configured such that the vehicle can move in all 6 DOFs using only 4 motors. Small actuators help to make the vehicle as small as possible allowing it to fit through narrow passages and to be easily portable. Another advantage of using fins is that they provide distributed propulsion, so reducing the amount of sediment brought up from the bottom. They also do not get tangled as easily as propellers and they are safe for the surrounding environment and for divers who may have to work together with the robot. To concurrently comply with the requirements of low final cost, small size and navigation in confined spaces, several sensors and vehicle modules have been custom developed during the project. U-CAT has 8 custom echo-sounders for obstacle detection and a custom hydrophone array for acoustic beacon localization. It also has custom buoyancy control pistons in each end allowing to actively trim the vehicle. From commercial sensors U-CAT contains a digital camera, several system health monitoring sensors, miniature Inertial Measurement Unit (IMU), depth sensor and an acoustic modem with range measurement capability. The battery allows at least 6 hours of autonomous operation. The control is implemented on a 1 GHz Quad-Core ARM computer using the Robot Operating System (ROS) middleware. The robot weighs around 19 kg, it is 0.6 m long and can dive to 100 meters.

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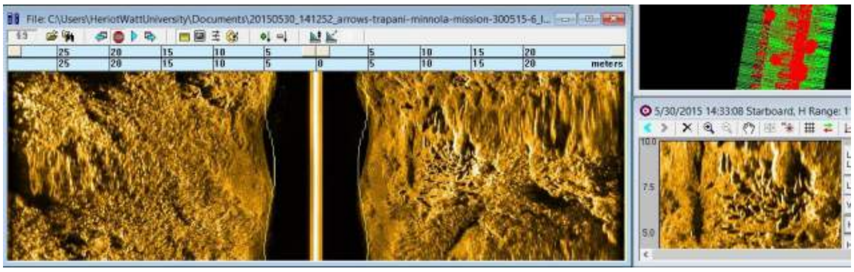

Figure 4. SSS image of the Amphoras at the Cala Minnola archaeological site

3. Final Demonstration in the Mediterranean Sea

During the trials throughout the ARROWS project, various missions were performed using the IVER-3 AUV. Its role as the search vehicle in the framework of ARROWS was to verify that given an approximate location of an archaeological site, we could accurately discover its location using an AUV and obtain good quality Side-Scan-Sonar (SSS) images; achieving these search goals allows closer inspection of the site using the ARROWS I-AUVs, MARTA or U-CAT. The first set of trials were performed in Sicily at a site called Cala Minnola. This site was known to contain archaeological artefacts of amphoras. In most locations, some prior information about the sub-surface topology is available. In some areas, this may be topographic maps or bathymetric data obtained by ships equipped with SSS. Even with such data known beforehand, caution should still be used when performing missions with AUVs. Using large-scale topographic maps, and therefore a low resolution, bathymetric map of the Cala Minnola site, we still assumed that the environment was initially unknown. Thus, the first mission was planned as reconnaissance, aiming to obtain detailed information of the natural features and sea floor. It was performed at a suitable altitude to ensure the safety of the vehicle and site, whilst able to record some sea floor data. As the uncertainty of the operating environment decreased, from the acquisition of more information, we could plan missions closer to the optimum SSS search parameters. Through experience using the IVER-3 AUV, we have found that an altitude of between 5-8 metres from the sea floor gives the best SSS images. The SSS images themselves can be used to determine the safety of the AUV by looking at the dark central region of the image. During one mission at Cala Minnola, shown in Fig. 4 which is very rocky, we noticed from the SSS image that the AUV only missed rocks by a approximately one metre. Learning of the steep rocks in the area, we determined safe mission parameters which allowed us to survey a large area and successfully find the Amphora site, shown in Fig. 4. The blurring in the image is hypothesized to be due to the high sea currents that were present in that area, coupled with the AUV's navigation being based only on dead reckoning (i.e. no acoustic positioning system was used). The AAG archaeologists at the sea trial were satisfied with the detail of the results.

After the acoustic search phase, MARTA was used as the inspection vehicle to acquire optical images of the site. Images of the field of amphorae in the Cala Minnola site were thus collected during autonomous missions and in Fig. 5 the related 3D reconstruction is reported (please see http://www.arrowsproject.eu/media-center/trials/3d-reconstructions-levanzo-sicily-and-rummu-quarry-estonia/) [8].

4. Final Demonstration in the Baltic Sea

The second set of tests was performed in Rummu, Estonia, at an artificial lake (flooded quarry).

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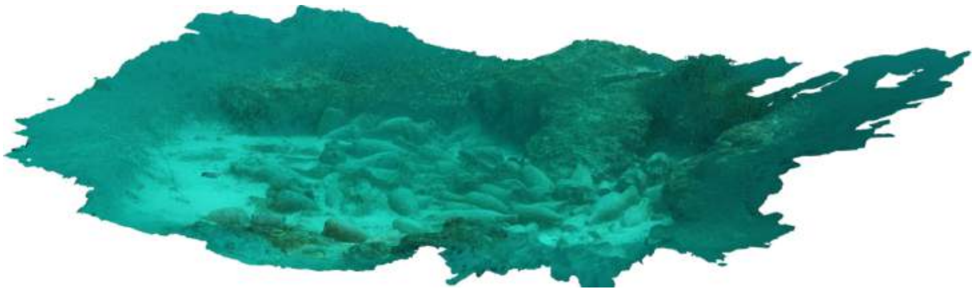

Figure 5. 3D reconstruction of Cala Minnola site from images acquired by ARROWS AUVs

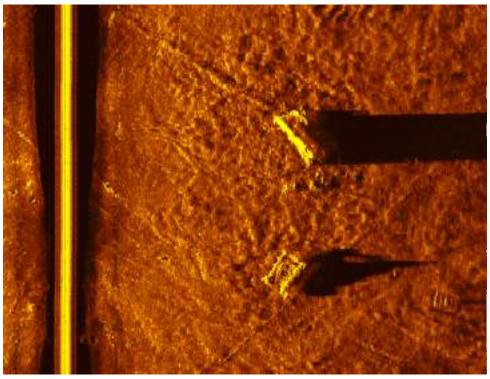

Figure 6. SSS image of the quarry machinery found in the Rummu quarry, Estonia

4.1. Acoustic and optical inspections in the Rummu quarry

The strategy employed during the Estonia trials was the same as used in the previous trials in Sicily. One of the main differences between the Cala Minnola site and Rummu quarry was their respective depth profiles. A substantial proportion of the Rummu quarry site is around ten metres depth or less. From the first SSS image, it was also apparent that there was a significantly larger number of features to be seen in the Rummu quarry than most sites we have visited at sea, consisting of roads, walls of buildings, and even traffic barriers were clearly visible in images taken of the quarry. During a mission which had been programmed to cover a large portion of the South-East bay of the quarry, several objects were particularly interesting. Through discussions with locals, we heard that there were several pieces of old quarry machinery that had not managed to be removed before the quarry was flooded but their locations were unknown. Having discovered likely candidates that could be the machinery, a mission was performed that took SSS images from all four sides of the objects. One of these images is shown in Fig. 6. From the objects' shape and size, including their height which from their shadows indicates that the top object is significantly larger than the bottom, it was determined that we had found the quarry machinery. Having obtained the geo-referenced data of the machinery, we could pass that data on to the IAUV operators who could inspect that area to validate that the coordinates we obtained using the IVER-3 AUV were correct, and to obtain further data of the machinery. After the acoustic search phase, the GPS points of the targets identified by the IVER3 were passed to MARTA. MARTA was thus used as the inspection vehicle (as in Sicily during the first Demo) to acquire optical images of the targets. An Inspection campaign was planned with MARTA AUV aimed at collecting optical images through its High Definition camera. The reference path and all the necessary mission parameters were defined through the graphical

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Human Machine Interface (HMI) developed within the project with the aim of simplifying the interaction of a non-specialized end-user (archaeologists in ARROWS) with the developed tools [1]. The inspection mission was composed of two different lawn-mower submissions: the first one with path legs parallel to the line connecting the two target points and the second one with path legs orthogonal to it. Processing the dataset collected in the Rummu quarry by means of Structure from Motion resulted in the generation of a 3D reconstruction given in Fig. 7.

Figure 7. 3D reconstruction of the Rummu quarry machineries from images acquired by ARROWS AUVs

4.2. Penetrating Machinery and Buildings with U-CAT

One of the located and inspected machines was also further investigated using the U-CAT vehicle. The machine has a small engine room whose interior is fully visible from the hatches on the top and side. Therefore, there was no need to perform a fully autonomous penetration mission. The U-CAT vehicle was remotely controlled using a live feedback from the onboard camera. As the goal was to demonstrate the performance in confined areas, the vehicle was guided to different locations in and around the mining machine. For example, Figure 8a shows the U-CAT entering the machine room. During the mission no major sediment disturbance caused by the robot was detected. Also, the robot did not get tangled and the operator was able to guide it to desired points of interest. However, the manual control of the vehicle was relatively difficult due to

[1] A video tutorial describing the usage simplicity of the ARROWS HMI was produced in the framework of the project and is available at the link: https://www.youtube.com/watch?v=fHNRCCMtgFE

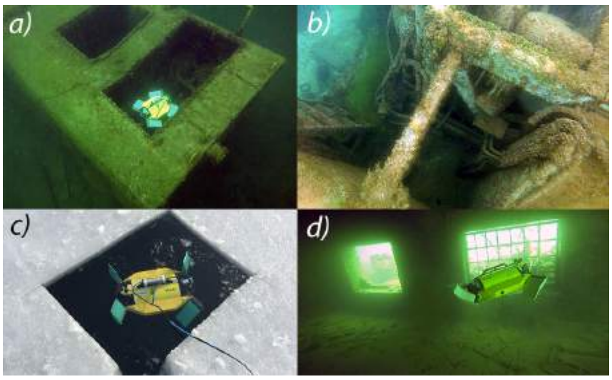

Figure 8. U-CAT on missions: a) Inspection of a machine room; b) Onboard camera image about the hydraulic mechanism of the machine; c) U-CAT launched through ice hole; d) autonomous inspection of a room

the high number of controllable DOFs. To simplify the inspection, the control was improved by implementing a stable autopilot for depth and yaw based on model-based controllers. To test the autopilot and to also test the vehicle in more difficult conditions, the mining machine inspection was repeated in March 2016. In March the lake was covered by 20 cm of ice. The robot had to be launched from a small hole cut into ice Figure 8c. Thanks to improved control and video quality, even more detailed visual information was gathered about the machine. Another mission with U-CAT was performed in Rummu quarry to demonstrate its usage in fully autonomous mode. The goal of the mission was to autonomously inspect a single room in one of the submerged prison buildings in the quarry (Figure 8b). The investigated room has dimensions of 10 m x 5.5 m. It has one large opening in one wall and several open doors and window holes on other walls. The U-CAT was launched by a diver from the large opening. In the first experiment the robot followed a predefined trajectory and then exited the building through the large opening. In the second experiment the vehicle also used its custom-made sonars to track and avoid the walls. The experiments demonstrate one possible scenario for using U-CAT in dangerous penetration missions.

5. Conclusions

The paper briefly summarized the main results achieved during the ARROWS (ARchaeological RObot systems for the Worlds Seas) European project, describing some of the tests at sea of the developed Autonomous Underwater Vehicle (AUV) technologies for archaeology. The tests started evaluating the performances of single AUVs before the final demos where the whole system, the heterogeneous fleet, was deployed at sea for a collaborative mission. Satisfying results at sea have been reached thanks to the collaboration among commercial vehicles and the ARROWS new prototypes. Good feedback were collected by the archaeologists during the tests, highlighting the potentiality of the proposed technologies.

Acknowledgments

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