Towards a Robust System Helping Underwater Archaeologists Through the Acquisition of Geo-referenced Optical and Acoustic Data

Benedetto Allotta[1], Riccardo Costanzi[1], Massimo Magrini[2], Niccolò Monni[1], Davide Moroni[2], Maria Antonietta Pascali[2], Marco Reggiannini[2], Alessandro Ridolfi[1], Ovidio Salvetti[2], and Marco Tampucci[2]

[1] Department of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139 Florence, Italy
[2] SILab, Institute of Information Science and Technololgies - CNR, Via G. Moruzzi 1, 56124 Pisa, Italy
maria.antonietta.pascali@isti.cnr.it

Abstract. In the framework of the ARROWS project (September 2012 - August 2015), a venture funded by the European Commission, several modular Autonomous Underwater Vehicles (AUV) have been developed to the main purposes of mapping, diagnosing, cleaning, and securing underwater and coastal archaeological sites. These AUVs consist of modular mobile robots, designed and manufactured according to specific suggestions formulated by a pool of archaeologists featuring long-standing experience in the field of Underwater Cultural Heritage preservation. The vehicles are typically equipped with acoustic modems to communicate during the dive and with different payload devices to sense the environment. The selected sensors represent appealing choices to the oceanographic engineer since they provide complementary information about the surrounding environment. The main topics discussed in this paper concern (i) performing a systematic mapping of the marine seafloors, (ii) processing the output maps to detect and classify potential archaeological targets and finally (iii) developing dissemination systems with the purpose of creating virtual scenes as a photorealistic and informative representation of the surveyed underwater sites.

1 Introduction

Marine water covers approximately the 72 % of the planet's surface and, being largely unexplored nowadays, it represents an unlimited source of discovery and knowledge in several fields, from ecology to archeology. Since the marine environment represents an extreme setting to the man, exploring these loca- tions typically requires large amounts of funding, knowledge and expertise, and finally, it can be seriously dangerous for the explorer. During the ARROWS project (end August 2015), funded by the European Commission, a modular Autonomous Underwater Vehicle (AUV) called MARTA, acronym for MARine Tool for Archeology, has been developed. The ARROWS project is devoted to advanced technologies and tools for mapping, diagnosing, cleaning, and securing underwater and coastal archaeological sites. MARTA AUV is a modular mobile robot designed and constructed according to the requirements formulated by a team of expert archaeologists operators, belonging to outstanding Cultural Heritage institutions (the Department of Cultural Heritage and Sicilian Iden- tity, and the Estonian Maritime Museum). MARTA is equipped with acousticmodems to communicate when submerged and it hosts two different payload sen-sor to capture data: a pair of synchronised digital cameras coupled with visible light as well as structured light (blue laser) illuminators and a forward looking multibeam echo-sounder or a side looking sonar.

The data collected during the mission campaigns will be processed in order to detect targets of interest located on the seabed. These data are affected by multiple typologies of distortions, relating to both systematic as well as environmental sources of corruption (Blondel 2009). Consider the example of the geometrical distortions affecting the sonar signal, such as the central black stripe in the side scan sonar maps (Fig. 2), generated by the acoustic propagation through the water column, or the random distortions in the sonogram formation, generated by unpredictable fluctuations in the AUV attitude.

Under the hypothesis that the noise can be properly filtered out and that the geometry distortions can be corrected by exploiting the geo-referencing of the data described in Sect. 2, the relevant goal is to analyze the output data to provide a highly informative description of the environment. The main approach adopted for the detection procedures is to emphasize the amount of regularity in the captured data. This can be pursued by exploiting machine learning algo- rithms that perform (i) the recognition of geometrical curves (ii) the classification of seafloor areas by means of textural pattern analysis and (iii) a reliable object recognition process performing the integration of the available multimodal data. Moreover the collected raw data, together with the analysis output results, will be stored to allow for an offline accurate analysis of the archaeological findings. This will represent a powerful tool for expert users as well as for disseminating to the general public the increased knowledge about the underwater sites.

2 MARTA AUV

The specific features required during a typical underwater archaeological mission concern two main situations: in a preliminary stage the AUV surveys a large scale area with the purpose of detecting interesting areas while, in case of a detected anomaly, a further survey stage is dedicated to obtain finer details about the detected site. Each configuration requires a proper choice in terms of the sensor suite to be installed on-board the AUV. To this purpose acoustic sensors are better exploited in large scale mapping of the environment while optical sensors work at their best in small range regimes. The two cited configurations are:

- Search AUV: AUV equipped with acoustic sensors, such as Side-Scan Sonar (SSS) or MultiBeam Echo Sounder (MBES), used for fast and large surveys, searching for targets of interest;

– Inspection AUV: the AUV aim is to reach the targets, identified as potentially interesting thanks to the data acquired by the Search AUV, and to acquire optical and/or acoustic images to obtain more details.

In order to fulfill the various requirements arising in an underwater archaeological mission, one of the main design criterion for MARTA has been the **modularity.** Depending on the mission to perform, MARTA is configurable with several payloads and different propulsion systems: this way, the vehicle can play both the role of search and inspection AUV. MARTA's payload can be:

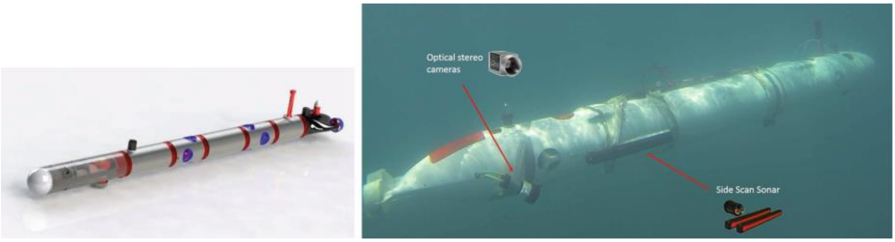

Fig. 1. MARTA final CAD (left); housing of the side scan sonar and of the cameras (right).

– Acoustic payload: a Multibeam Echo Sounder (MBES - Teledyne BlueView M900) is housed in the bow;
– Optical payload: MARTA houses a couple of Basler Ace cameras, a C-laser Fan from Ocean Tools, four illuminators.

MARTA has 5 degrees of freedom which can be fully controlled by means of 6 actuators (electrical motors plus propellers). More in detail they consist of 2 rear propellers, 2 lateral thrusters and 2 vertical thrusters. The described actuation system enables the vehicle to perform hovering. The technical features of MARTA are summarized in Table 1; Fig. 1 (left) shows the final 3D CAD outline of MARTA AUV.

The first sea trials of MARTA AUV are scheduled fro the end of March 2015, but the vehicle payload, both acoustic and optical, has been already tested at sea. This was possible by exploiting the **Typhoon** (see Fig. 1 right), an AUV that has been designed, developed and built by the UNIFI MDM Lab in the frame- work of the previous THESAURUS project (Allotta et al. 2014a; Allotta et al. 2014b). Typhoon AUV proved to be an useful tool for archaeologists and already performed several missions at sea with suitable payload on board. Figure 2 shows an example of side scan sonar (SSS) data captured during a Typhoon mission at the Baratti Gulf, Italy, July 2014 (the Caligola wreck is visible in the right channel). The acquisition system is based on two different PC housed on board the vehicle:

Table 1. MARTA AUV technical features.

AUV parameter	Value
Reachable depth (m)	120
Maximum longitudinal speed (kn)	4
Battery autonomy (hr)	$4 \div 6$
Length (m)	$3 \div 4$
External diameter (in)	7
Weight (kg)	~ 90
Power supply voltage (V)	24 (LiPo batteries)
Main components material	Anticorodal (corrosion-resistant **Al** alloy)
Redundant propulsion system	6 thrusters plus 2 buoyancy modules
Hovering capability	5 DOFs (except roll) fully controllable

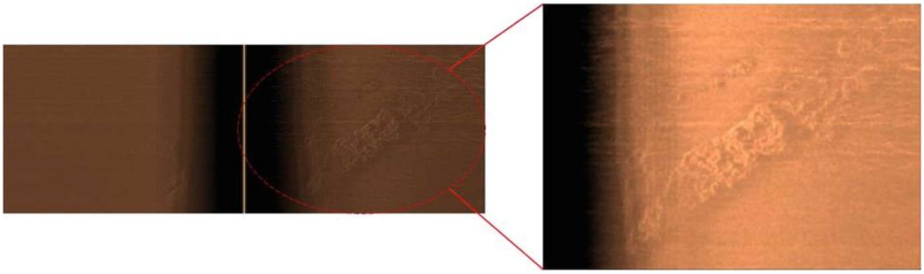

Fig. 2. Acoustic image from SSS of the Caligola wreck (right channel), Gulf of Baratti, Italy

- Vital PC: it is a very reliable industrial PC dedicated to the vital aspects that include the motion control and navigation tasks in addition to the unsafe conditions detection and response. Its capabilities are not very high as this kind of task is not very demanding from a computational point of view;
- Payload PC: it is a high performance SBC (Single Board Computer) with an i7 processor dedicated to the acquisition and the process of high amount of payload data as optical and acoustic images are.

From the software point of view, all the various modules are interfaced by means of ROS (Robots Operating System, http://www.ros.org/), a popular middleware that allows a simplified management of the data flow within the system. ROS is used also to ensure an accurate synchronization of all the available data; each piece of data is logged through the so call rosbag method along with a timestamp corresponding to the instant when it has been generated. By means of the comparison between the timestamp associated to payload data and the one associated to the navigation state, calculated through the navigation filter for the AUV pose estimation running in real-time, an accurate geo-referencing of the payload data is available since the end of the mission. Also raw navigation data (not processed output data from navigation sensors) are logged with timestamp so that, in case the real time pose estimation filter fails, payload data geo-referencing can be achieved in post processing. The navigation strategy used to guarantee a valid georeferencing of the payload data is based on two independent algorithms, respectively an orientation estimation one and a position estimation one. The former exploits the use of the 3D accelerometer, the 3D gyroscope and the 3D magnetometer mounted on board; data from these sensors are fused within a Nonlinear Complementary Filter based on Mahony et al. (2008). The latter, exploiting all the navigation sensors available, follows a Kalman filtering approach within an Unscented Kalman Filter developed in the framework of the ARROWS project itself (Allotta et al. 2015).

3 Payload Data Processing

The main goal of the AUV mission is to perform a systematic mapping of the marine seafloors (e.g. in Elibol et al. (2014), for the optical mapping) and to detect and classify potential archaeological targets. To that aim the underwa- ter vehicles will be equipped with two acquisition payloads (as described in the previous section), providing complementary information about the surrounding environment: acoustic sensors are exploited to create large scale maps of the environment while cameras provide more detailed images of the targets. Since the two sensor typologies operate on different principles the captured data are affected by different distortions, relating to both systematic as well as environmental sources of corruption. The cameras introduce geometrical distortions in the images because of the propagation of electromagnetic waves through the optical unit. Moreover the optical signal is affected by strong degradation due to energy absorption in the water medium. On the other hand acoustic sonars are affected as well by geometrical distortions. That is due to the peculiar percep- tion of the environment: e.g. side scan sonar maps contain a central black stripe which is generated by the propagation of acoustic waves through the water col- umn. That represents useless piece of information that has to be erased in order to restore the correct geometrical properties of the data. Also the fluctuation in the pose of the vehicle hosting the sensors may represent a relevant source of geometry distortion of the data. In case of strong oscillations of the vehicle induced by intense waves or currents this can represent a dominant issue.

This issue highlights the strong need for the synchronization of the optical and acoustic data with the navigation data records, in order to get a proper correction. Under the hypothesis that the whole set of noise sources can bereduced by proper restoration and geometry correction techniques the successivegoal is to analyse the output data to provide an informative description of the environment.

3.1 Geometry Assessment

The ARROWS project is conceived to supply with technological tools the archaeological operators, hence a scene understanding procedure has to be mainly focused on man-made object recognition tasks. To that purpose the adopted criterion is to highlight the regularity content in the data. In this framework we consider regular those areas containing parts of primitive curves, like lines, circles and ellipses. Moreover regularity can be found in repeating patterns in the image spatial intensity.

Based on those features, we can perform attentive analysis of the environment by giving to an area a label of interest proportional to the regularity content: more regular areas are marked with higher ranks while chaotic and unstructuredarea will be marked with low ranks.

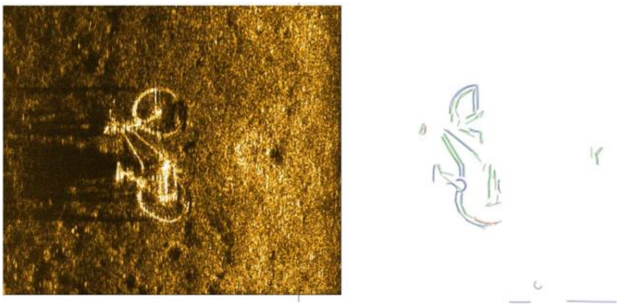

Fig. 3. Application of the curve detection algorithm to a side scan sonar image detail (image taken from http://www.jwfishers.com/).

The assessment of primitive curves segments in an image is a typical computer vision issue that has been tackled in many ways. In order to fulfill the curve detection purpose, a dedicated procedure has been developed. The implemented algorithm is based on a statistical approach in order to provide the system with enough reliability and computational performances. The application of the algorithm, based on the Gestalt theory (Desolneux et al. 2004; Patraucean et al. 2012), is more thoroughly described in Moroni et al. (2013a). Some results are shown in Fig. 3.

3.2 Texture Analysis

Texture is a descriptor of the surface appearance of objects. This parameter can be exploited to discern between different kinds of objects and to assign each of them to a specific class. In the special case of underwater mapping, textural analysis is employed to classify the surveyed environment into seafloor categories (sand, rock, vegetation). This enables the detection of anomalies that can be related to potentially interesting objects.

Within the many descriptors available in the literature we chose a method based on the Gabor filters (Jain et al. 1991). Mathematically speaking a Gabor filter is a 2D sinusoid, with specific orientation and frequency values, modulated by a Gaussian function. The convolution of this filter with an image results in a map where the regions exhibiting frequency and orientation values similar to the filter ones are emphasized. By varying frequency and orientation and repeating the convolution operation a set of filter responses is obtained. Those responses can be clustered according to the dominant component. This way every pixel in the image will be assigned to a specific class. The application of Gabor filters for textural analysis purposes is illustrated in Fig. 4.

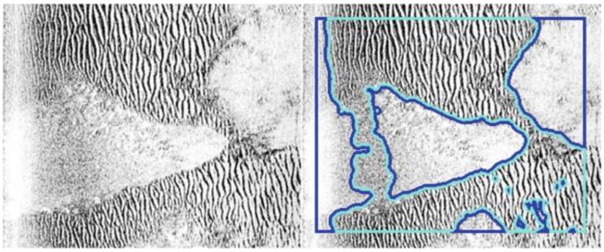

Fig. 4. SSS map segmentation by exploiting of a Gabor filtering technique (image taken from http://www.ise.bc.ca/)

3.3 Data Integration

As stated in the previous sections, each sensor employed in the survey missions will provide an individual description of the environment. As far as a robust object recognition process is pursued, it is interesting to conceive a syn- thesis structure summarizing all the informative content related to an area of the seabed. This can be formally expressed by introducing a multi-dimensional map, made up of multiple layers. A point in this map gives details about the whole information available for the corresponding point in the world (Moroniet al. 2013b). This refers to information concerning (i) the raw captured data, (ii) the results of data analysis algorithms and (iii) the bathymetry collected by proper sensors or estimated by computer vision procedures. It is expected that considering the whole set of available information can be an efficient way to perform a robust object recognition, reliable with respect to false alarms rejection. An example of data integration result, obtained by stitching the camera images mosaic on the multi-beam bathymetry is illustrated in Fig. 5.

4 3D Rendering and the Virtual Environment

The whole set of data acquired in each acquisition campaign is the base for (i) the 3D modelling of the archaeological inspected, and (ii) the virtual reconstruction of the archaeological site where the finds are located. These two outputs are of great importance for both the community of archaeologists and the gen- eral public. The availability of detailed data about an object of interest allows

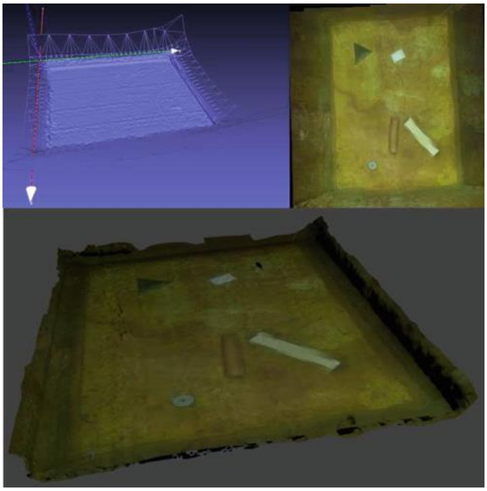

Fig. 5. Bathymetric map, obtained by means of a multi-beam echo-sounder, integrated with an optical mosaic. The data have been captured during an experiment performed in the small pool facility of the Ocean Systems Lab, Heriot Watt University, Edinburgh (Scotland)

Fig. 6. Detailed reconstruction of an amphora: only mesh (left) and textured (right)

building a detailed 3D model to be studied by experts. The visualization and comparison with existing findings will lead to a deeper knowledge of the inspected site without any risk for the people involved in the acquisition campaign. The method used for the 3D modelling is based mainly on multi-view stereo algorithms applied to the optical data. The detailed reconstruction of the mesh (geometric structure) and the texture (appearance) of a single object of interest will be semi-automated in order to fulfill the archaeological validation (see Fig. 6). The virtual reconstruction will be interactive (enabling the user to explore the environment) and possibly multimodal (linking videos, pictures, text, 3D models to specific points of interest in the scene). This way the fruition will ensure an immersive and informative setting for promoting access and exploiting the rich underwater cultural heritage. The reconstructed mesh is refined through advanced 3D computer graphics tools (e.g. Blender, MeshLab). Then the meshes (objects and terrain) are integrated together in a virtual environment exploiting advanced game engine functionalities (e.g. Unity) in order to obtain a more immersive and better detailed scene (see Fig. 7). The scene fruition can be per- formed also through the most recent 3D interaction devices, like Oculus Rift (see Fig. 8), and gestural interfaces, like Kinect and Hot Hand.

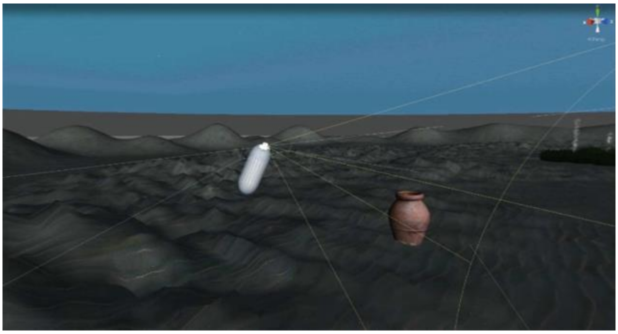

Fig. 7. Scene reconstruction exploiting Unity game engine.

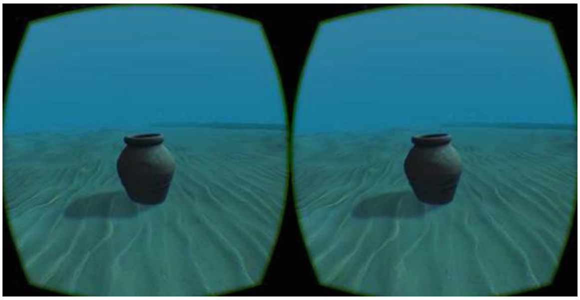

Fig. 8. View of the 3D Virtual Environment through Oculus Rift

5 Conclusions

The robotic and automation technology presented in this paper will make easier the underwater archaeologist work, carried out in a hostile and complex environment. The archaeologist will be provided with techniques to perform indi- rect measurements and to formulate historical interpretations on the findings. Moreover, in order to disseminate knowledge regarding the underwater cultural heritage and to increase the sensitivity for its preservation, the developed tools allow to address different audiences, including the general public. In particular, one of the purposes of the project is to devise new dissemination channels making use of 3D immersive environments to make more attractive the collected information. In the next months, the developed methodology will be tested by organizing specific campaigns in two European sites, one in Italy, in the Egadi Archipelagos, and one in the Baltic sea. All the collected data will be processed using the methods reported in this paper and will be used for assessing the validity of our approach. As a result, a set of 3D scenes will be produced, with the aim of replicating the experience of wreck exploration and survey.

The activity described in this paper has been supported by the ARROWS project, funded by the European Union 7th Framework Programme for research, technological development and demonstration under grant agreement no. 308724. The authors would like to thank Dr. Pamela Gambogi, Executive Archaeologist and Coordinator of the Underwater Operational Team of the Tuscany Archaeo- logical Superintendence. The authors would also like to thank Prof. Yvan Petillot and Prof. David Lane from Heriot Watt University of Edinburgh, for kindly pro- viding access to the facilities of the Ocean Systems Laboratory.

References

Allotta, B., Costanzi, R., Meli, E., Pugi, L., Ridolfi, A., Vettori, G.: Cooperative localization of a team of AUVs by a tetrahedral configuration. In: Robotics and Autonomous Systems, vol. 62, pp. 1228–1237. Elsevier (2014)

Allotta, B., Pugi, L., Bartolini, F., Ridolfi, A., Costanzi, R., Monni, N., Gelli, J.: Preliminary design and fast prototyping of an autonomous underwater vehicle propulsion system. Proc. Inst. Mech. Eng., Part M, J. Eng. Marit. Environ. (2014). doi:10.1177/1475090213514040

Allotta, B., Caiti, A., Chisci, L., Costanzi, R., Di Corato, F., Fantacci, C., Fenucci, D., Meli, E., Ridolfi, A.: Development of a navigation algorithm for autonomous underwater vehicles. In: IFAC Workshop on Navigation Guidance and Control of Underwater Vehicles (NGCUV 2015), Girona, Spain (2015)

Blondel, P.: The Handbook of Sidescan Sonar. Springer Praxis Books, New York (2009)

Desolneux, A., Moisan, L., Morel, J.M.: Gestalt theory and computer vision. In: Seeing, Thinking and Knowing. vol. 38, pp. 71–101. Kluwer (2004)

Elibol, A., Kim, J., Gracias, N., Garcia, R.: Efficient image mosaicing for multi-robot visual underwater mapping. Pattern Recognit. Lett. **46**, 2026 (2014)

Jain, K.A., Farrokhnia, F.: Unsupervised texture segmentation using gabor filters. Pattern Recognit. **24**(12), 1167–1186 (1991)

Mahony, R.E., Hamel, T., Pflimlin, J.M.: Nonlinear complementary filters on the special orthogonal group. IEEE Trans. Autom. Control **53**(5), 1203–1218 (2008)

Moroni, D., Pascali, M.A., Reggiannini, M., Salvetti, O.: Curve recognition for underwater wrecks and handmade artefacts. In: IMTA13, 3rd International Workshop on Image Mining. Theory and Applications (2013)

Moroni, D., Pascali, M.A., Reggiannini, M., Salvetti, O.: Underwater scene understanding by optical and acoustic data integration. In: Proceedings of Meeting on Acoustics, vol. 17 (2013)

Pătrăucean, V., Gurdjos, P., von Gioi, R.G.: A parameterless line segment and elliptical arc detector with enhanced ellipse fitting. In: Fitzgibbon, A., Lazebnik, S., Perona, P., Sato, Y., Schmid, C. (eds.) ECCV 2012, Part II. LNCS, vol. 7573, pp. 572–585. Springer, Heidelberg (2012)