Acoustic Data Analysis for Underwater Archaeological Sites Detection and Mapping by Means of Autonomous Underwater Vehicles

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***Abstract*—In the framework of the ARROWS project (FP7 Environment 308724, September 2012 - August 2015), venture funded by the European Commission, modular Autonomous Underwater Vehicles (AUVs) have been developed to the main purposes of mapping, diagnosing, cleaning, and securing of underwater and coastal archaeological sites. These AUVs consist of modular mobile robots, designed and manufactured according to specific directions formulated by a group of expert archaeologists, the Archaeological Advisory Group (AAG). A preliminary fleet of mobile robots, with supplied functionalities that can be adjusted on the mission purpose, has been put together. The vehicles are typically equipped with acoustic modems to communicateduring the dive and with different payload devices to sense the environment: a pair of synchronized digital cameras operating in the visible light range, a structured light source (blue laser) plus led illuminators and, depending on the mission requirement, a multibeam forward looking echo-sounder or a side looking sonar. These sensors represent appealing choices to the oceanographic engineer since they provide complementary information about the surrounding environment. Generally speaking acoustic sensors are exploited to create large scale maps of the environment while cameras provide more detailed images of the targets. The main goal of the ARROWS missions is to perform a systematic mapping of the marine seafloors and to process the output maps to detect and classify potential archaeological targets.**

I. INTRODUCTION

Mapping the oceans’ floors represents an extremely demanding task to the man. The peculiar environmental setting is for the most part out of reach to human operators because of the hard environmental conditions that make the survey complex and dangerous. Nevertheless mapping the seafloors represents a relevant task that is of typical concern to many involved operators, such as biologists, engineers and archaeologists.

It is known that the oceans’ floors host a large amount of cultural heritage as a consequence of shipwreckages that took place during the past ages. The main goal of the FP7 project ARROWS (ARchaeological RObot Systems for the World’s Seas [1]) is to supply techniques and tools to support the underwater archaeologists’ work by implementing the relevant tasks that make up the workflow of an archaeological mission. To these aims a new generation of Autonomous Underwater Vehicles have been designed and implemented. These vehicles are equipped with properly selected sensors with the purpose of collecting data from the surveyed environment.

The data collected by the AUVs 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. Under the hypothesis that the whole set of noise sources can be reduced by the restoration and geometry correction techniques that will be detailed in the following sections, the relevant goal is to analyze the output data to provide a highly informative description of the environment. The main approach adopted in the detection procedure is to emphasize the amount of regularity in the captured data. This can be pursued by exploiting computer vision and machine learning algorithms 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 multi modal data. Moreover the collected raw data, together

Fig. 1: MARTA Autonomous Underwater Vehicle

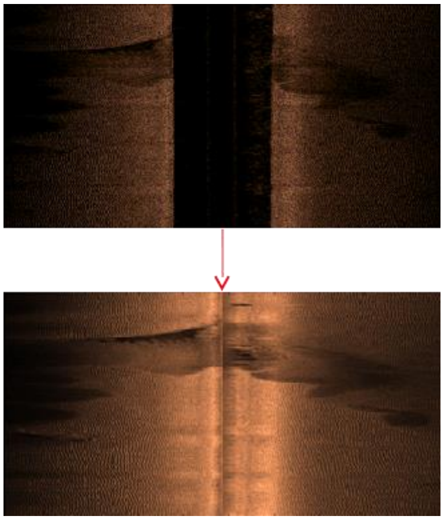

Fig. 2: Sidescan sonar map. Slanted and Ground corrected coordinates.

with the scene understanding algorithms 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 underwater sites.

The paper outline is arranged as follows: section II concerns a synthetic description of the vehicle and its main features, in the main section III all the implemented procedures concerning data conditioning and pre-processing, the algorithms performing the scene understanding tasks and the map generation of the surveyed scenario are detailed, finally section IV focuses on the described activity and the related conclusions.

II. VEHICLE SECTION

MARTA (MARine Tool for Archaeology) is a modular AUV designed and developed by the University of Florence. 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 be performed and will be easily deployable from a small boat; the vehicle is modular and has a totallength of about 3 m (depending on its configuration), an external diameter of 7 inches and an in-air weight of about90 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 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 mud that can create issues for the acquisition of optical and acoustic data (figure 1).

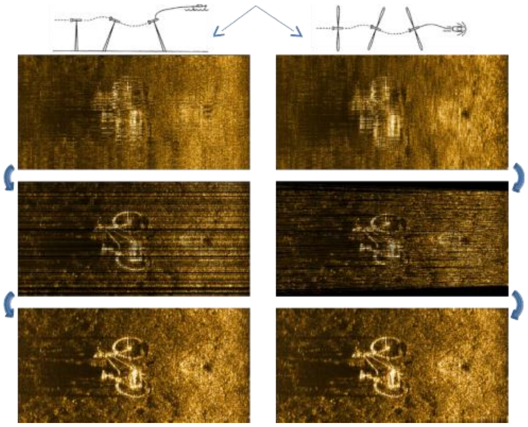

Fig. 3: Sidescan sonar map. Attitude distortions and corresponding restoration.

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 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).

III. DATA PROCESSING

The output data returned by the payload sensors must undergo multiple processing stages, starting from the enhancement of the raw output signal, ending with specific computer vision and image processing techniques with the purpose of extracting as much information as possible from the collected data. A preliminary step in the manipulation of the data concerns a set of operations devoted to the restoration of the signal and to the enhancement of the relevant properties, whose integrity is crucial for the correct understanding of the scenario. In our specific case we are concerned with correcting those systematic geometrical distortions introduced in the signal due to the peculiar perception of the environment performed by the employed sensors. Consider the example of the geometrical distortions affecting the side scan sonar mapping, such as the central black stripe in the raw output sonogram, which is generated by the acoustic wave propagation through the water column (figure 2), or the random distortions in the sonogram

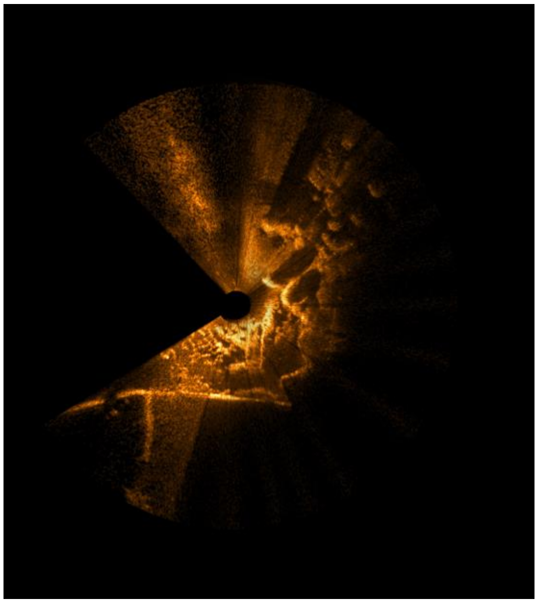

Fig. 4: Forward Looking Mosaic Map. The image results from the stitch process of 17 frames captured by a **Blueview MB-P900** sonar during an experimental campaign performed in Israel, at the Caesarea ancient harbour.

formation, caused by the unpredictable fluctuations in the AUV attitude (figure 3).

Auxiliary sensor devices, such as inertial measurement units, gyrocompass, DVL, etc., are exploited to provide the vehicle's position and pose measurements during the acquisition. This additional information can be profitably used to restore the corrupted data. Many researchers devoted their work to the restoration of the correct properties of the sonar signal (see for example [2]).

In the underwater mapping field this represents an important step to be performed before applying algorithms aiming at a high level understanding of the surveyed scenario. Indeed the performance of an automatic understanding system, which involves algorithms borrowed from the computer vision, machine learning and image processing background, strongly depends on the quality of the captured data. Actually we have to be confident that the data, either considered as a straight raw output of the sensor or as the result of the pre- processing stages, exhibit the highest achievable quality. This is an auspicious precondition, that should be pursued in order to allow the dedicated processing units to automatically detect those features and attributes of conspicuous importance for the understanding process.

A. Sonar Mapping and 3D Reconstruction

The underwater mapping task suffers from a lack of large range visibility due to a combination of different factors. First of all, the energy of the optical and acoustic perturbation generated by the sensors decreases proportionally to the inverse of the squared distance, due the spherical spreading of the waves. Moreover the underwater medium affects the optical wave by strongly modifying its spectrum before the signal is collected by the camera. This causes a heavy alteration of the perceived signal since a large percentage of the visible frequencies that constitute the optical data are filtered out. This limitation reduces the maximum operational range ofthe sensor to few meters. Furthermore the image is usually corrupted by strong haze effects, which hardly distort the camera mapping process. This sensing limitation can be tackled in case a large set of data relating to the same scenario is available. By exploiting computer vision algorithms that perform the alignment and the integration of multiple maps it is possible to generate a map representing the entire surveyed environment (**mosaic**), obtaining an overall view of the mission area. Applying a mosaicking procedure usually involves the recognition of relevant features contained in the data, such as SIFT or SURF features. Then the corresponding features appearing in multiple maps are matched and exploited to estimate the geometry transform that maps the set of images in a common frame. The transformed maps are finally stitched together to generate the mosaic map. In the unfavourable case that the detectable number of features is too low due to bad quality or very noisy data the feature matching may become an unfeasible operation. Under that condition the additional data collected by auxiliary sensors measuring the vehicle attitude may help towards the estimation of the required geometrical transform.

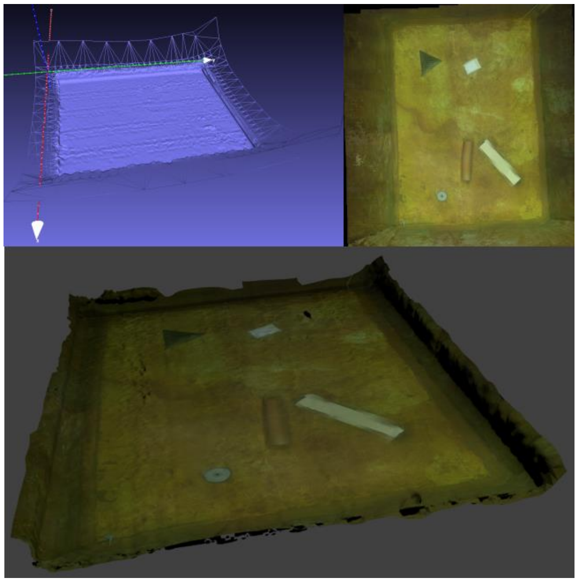

Fig. 5: Heterogeneous dataset captured during an experimental session at the small pool of the Ocean Systems Lab, Heriot Watt (Edinburgh). In the left upper part the pool bathymetry map captured by the **Blueview MB-2250**, is illustrated. The right upper part represents the optical mosaic obtained bystitching the GoPro images of the pool floor while the lower part represents the integration between the bathymetric map and the optical mosaic.

To test the mosaicking algorithm, a set of acoustic data has been captured during an experimental campaign performed in two weeks of sea trials in Israel. The mission has been funded by the Office of Naval Research Global - ONR-G of the U.S. Navy and supervised by the Marine Archaeology Unit, Israel Antiquities Authority - IAA, and took place from June 17th to July 1st 2014 in Akko and Caesarea (Israel). During the

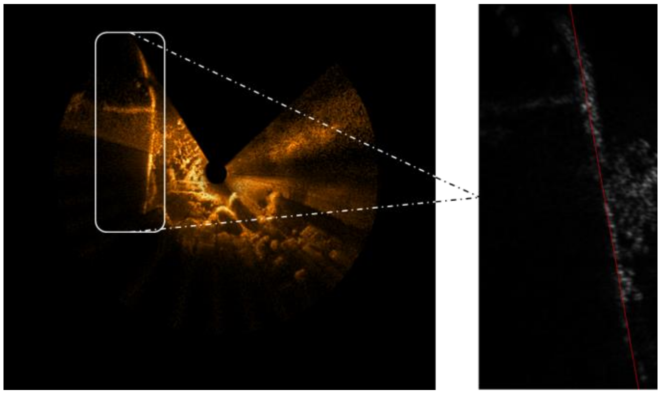

Fig. 6: Line detection on the mosaic of figure 4. A detected line belonging to a pier wall structure is emphasized.

mission also two typhoon-class AUVs have been employed ([3]). In that circumstance a multibeam forward looking sonar sensor (**Blueview MB-P900**) has been tested to survey a pier wall in the nearness of the Caesarea harbor and part of the data has been processed to obtain a large scale map of that area. The result of the mosaicking process is illustrated in figure 4.

As previously mentioned the choice of the acoustic payload sensors to be employed during the missions depends on the specific purpose of the mission itself and on the environmental scenario that has to be surveyed. The side scan sonar and the multibeam forward looking sonar return large scale maps of the seafloor that are typically processed to detect obstacles, objects or areas of the seafloor showing interesting features. On the other hand the multibeam echosounder returns detailed 3D bathymetry maps of the inspected area in the form ofpoint cloud data. To test the bathymetry survey performance ofthe multibeam echosounder an experimental dataset has been captured in the small pool environment of the Ocean Systems Laboratory, Heriot Watt University of Edinburgh (Scotland). The maps collected by the **Blueview MB-2250** have been processed to extract the linear subset of the data corresponding to the intersection between the sensor beam and the pool floor. Then, by integrating these data with the pose measurements of the sensor, it was possible to perform the 3D alignment of the point cloud. The point cloud obtained this way has been further processed to generate the 3D mesh of the terrain (figure 5, upper left), and the result has been integrated with the optical mosaic of the floor (figure 5, upper right). The optical dataset has been obtained by employing a **GoPro** camera, collecting data simultaneously with the **MB-2250**. The result of the fusion between bathymetry and textural information is represented in the lower part of figure 5.

B. *Regularity in the data*

A relevant activity has been developed bearing in mind the primary goal of an archaeological mission, that is the detection of potential structures related to human made objects. The automated system that should perform this task, must recognize specific features exhibited by the selected candidates and put forward an hypothesis on the manmade object's nature. Hence a set of proper criteria has to be chosen in order to grab the most relevant objects' attributes. Within the multiple possible choices we oriented our approach towards assessing the presence of regularity features contained in the captured data. These regularity attributes may refer to the geometric shapes that define the contours of objects as perceived by the sensor device, hence fragments of primitive curves such as lines, circles or ellipses.

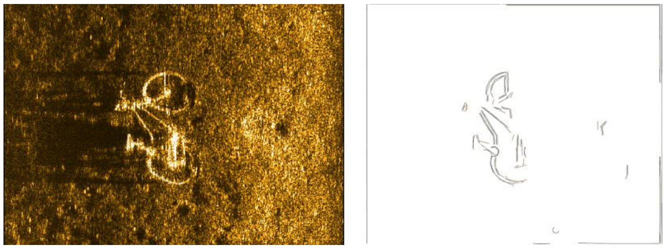

Fig. 7: Geometry detector applied on side scan sonar map (image taken from http://www.jwfishers.com/).

On the other hand we are also concernced about detecting patterns in the image that may be grouped together in terms of similar intensity variation patterns. These patterns may be detected by exploiting their specific frequency content, which can play therefore the role of a discriminative signature. By recognizing specific linear combinations of bidimensional wavelet functions we can cluster pixels and classify those subsets in an image exhibiting the same frequency features as belonging to the same category.

1) Geometry assessment: Starting from the hypothesis that a high concentration of regular curves is a marker for the presence of man-made objects or shipwrecks, we focused our work on the automatic detection of elementary geometric features (line segments, elliptical arcs) in images. This represents a classical issue in the Computer vision field and it has been thoroughly tackled and discussed by the scientific community (see for example [4], [5]).

The current procedures for geometric features recognition can be roughly classified into two categories: *Hough-based* and *edge chaining* methods. The main difference between the typical use case found in the literature and our experience is that these algorithms, generally designed and tested on optical images, have to be applied on acoustic maps captured by sonars. Compared to optical images, sonar maps feature substantial differences in terms of intensity, resolution and geometry perception, and they are typically corrupted by peculiar noise typologies, such as speckle noise (see for example [6], [7]).

The Hough-based algorithms make use of implementative variations of the Hough transform. These methods ensure that pixels belonging to the same geometric structure are mapped to the same point into an appropriately defined parameter space. Concerning this class of algorithms the required computational time grows proportionally with the number of the parameters of the sought curve so, in our case, it is a good choice for detecting lines, but not for detecting circular or elliptical shapes.

We exploited Hough based procedures to detect the presence of structures featuring for the most part linear shapes, such as architectural elements or remains of ancient walls. This

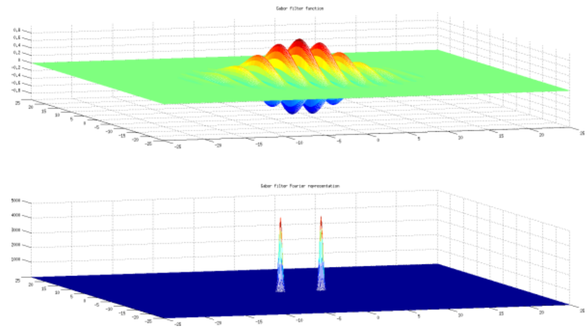

Fig. 8: Gabor filter plot (above) and its Fourier transform (below).

was the case of the Israel mission mentioned in section III-A, during which the captured acoustic dataset has been processed to detect the presence of primitive curves. A first result is presented in figure 6, where the red line identifies a pier wall structure detected by the algorithm.

A second class of detection methods relies on edge chaining techniques, which is extensively based on the detection of specific properties of the sought features, such as straightness for line segments or curvature properties for ellipses.

These algorithms usually start with a seed pixel or a group of pixels. Later, additional pixels are added, provided that they obey some geometric properties of the sought feature. Starting from the work presented in [8] we implemented a procedure for primitive curves recognition purposes. In that paper the authors describe the implementation of ELSD, a parameterless algorithm based on the Gestalt theory, whose applications to computer vision issues had already been discussed in [9]. More details about the implemented curve recognition procedure and its application to archaeological sites detection can be found in [10], [11].

We went through promising performances of ELSD on synthetic and natural optical images, as stated in [12]. Promising results on sonar maps can be achieved and exploited to perform attentive analysis of the data (figure 7). Once more it is worth reminding that a correct restoration of the signal, as illustrated in figure 3, may affect critically the curve recognition process. This is even more important in case the surveyed environment features large varieties of shapes and contours, such as archaeological sites including amphoras, plates and complex wrecks.

2) Texture analysis: A mathematical tool that has been succesfully employed to perform the texture analaysis of an image is the 2D Gabor wavelet function, defined by equation 1 (figure 8). As mentioned above the surface appearance of the objects located in the surveyed environment can be exploited to perform image segmentation and classification. More in particular the spatial frequency content of the image is strictly connected to the objects' surfaces as they appear in the map.

$$h(x', y') = \exp\left[-\frac{1}{2}\left(\frac{x'^2}{{\sigma_x}^2} + \frac{y'^2}{{\sigma_y}^2}\right)\right]\cos(2\pi u_0 x') \qquad (1)$$

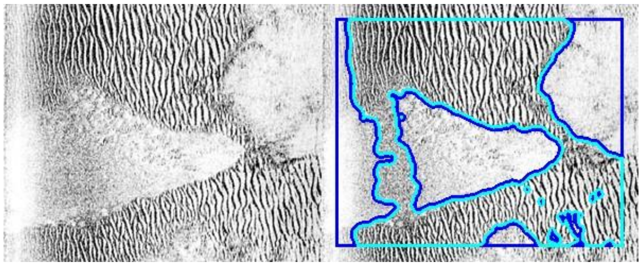

Fig. 9: Texture classification of side scan sonar maps by means of Gabor filtering (image taken from http://www.ise.bc.ca/).

The wavelet orientation can be adjusted by properly rotating the coordinate system (equation 3).

$$\begin{aligned} x &= \ x' \cos\theta_0 + y' \sin\theta_0 \\ y &= -x' \sin\theta_0 + y' \cos\theta_0 \end{aligned} \qquad (3)$$

In the Fourier domain the transformed Gabor wavelet is represented as a 2D Gaussian function centered at the specific u_0 *radial frequency* value. The product of the Fourier transform of the captured map with the Fourier transform of theGabor filter results in the emphasis of the common frequency components. This allows to consider the Gabor wavelet as a bandpass filter centered on the specific wavelet band.

The filtering operation consists in the convolution of the wavelet with small windows centered on the image pixels. This operation is repeated by varying u_0 and θ_0, then, for every convolution result, specific features are computed, such as the energy of the filtered image [13]. Hence for everyimage pixel we obtain a set of features describing the pixel frequency content. The similarity between pixels is assessed by comparing the computed feature vectors, comparison thatis based on a proper proximity criterion. To this aim popu-lar clustering algorithms, like K-means ([14], [15]), can be successfully employed. The final segmentation of the map is

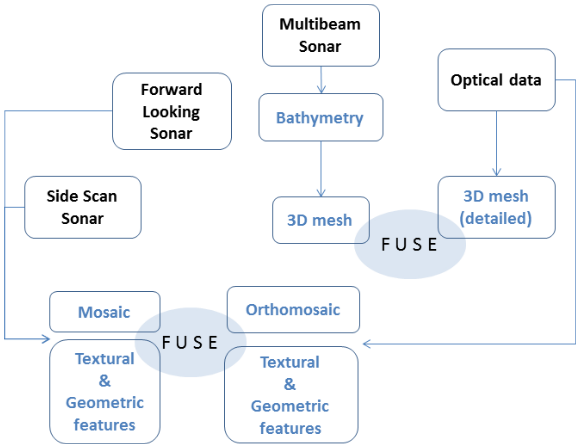

Fig. 10: Multiple processing methods employed to perform the understanding of the seafloor environment.

performed by repeating the described operation for every pixel. An example of the result of this process is represented in figure 9.

IV. CONCLUSIONS

The robotic and automation technology presented in this paper will make easier the underwater archaeologists' work, carried out in a hostile and complex environment. The many implemented procedures aim at providing the archaeologists with methods to perform a thorough analysis of the heterogenous sensor data returned by the payload sensors. The proposed processing options (figure 10) aim at the fulfillment of all the archaeologist's requirements and enable him to perform indirect 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 isto 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.

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REFERENCES

[1] B. Allotta et al., *The ARROWS project: adapting and developing robotics technologies for underwater archaeology*, IFAC Workshop on Navigation Guidance and Control of Underwater Vehicles (NGCUV 2015), 2015

[2] D. T. Cobra, A. V. Oppenheim, J. S. Jaffe, *Geometric distortions in sidescan sonar images: a procedure for their estimation and correction*, IEEE Journal of oceanic engineering, Vol.17, No. 3, July 1992

[3] B. Allotta, L. Pugi, F. Bartolini, A. Ridolfi, R. Costanzi, N. Monni, J. Gelli, *Preliminary design and fast prototyping of an autonomous underwater vehicle propulsion system*, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 2014.

[4] P. V. C. Hough, *Machine Analysis of Bubble Chamber Pictures*, Proc. Int. Conf. High Energy Accelerators and Instrumentation, 1959

[5] D. Ballard, *Generalizing the Hough transform to detect arbitrary shapes*, Pattern Recognition, vol. 13, no.2, 111-122, 1981

[6] P. Blondel, *The Handbook of Sidescan Sonar*, Springer Praxis Book, 2009

[7] X. Lurton, *An introduction to underwater acoustics, principles and applications*, Praxis Springer Books, 2010

[8] V. Patraucean, P. Gurdjos, R. G. von Gioi, *A Parameterless Line Segment and Elliptical Arc Detector with Enhanced Ellipse Fitting*, ECCV (2), Lecture Notes in Computer Science, Springer, 572-585, 2012

[9] A. Desolneux, L. Moisan, J.M. Morel, *Gestalt theory and Computer Vision*, Seeing, Thinking and Knowing, Kluwer, 71-101, 2002

[10] D. Moroni, M. A. Pascali, M. Reggiannini, O. Salvetti, *Curve recognition for underwater wrecks and handmade artefacts*, Proceedingsof IMTA 4, 4th international Workshop on Image Mining. Theory and Applications (Barcelona, 23rd February 2013), 14 - 21, SCITEPRESS, 2013

[11] D. Moroni, M. A. Pascali, M. Reggiannini, O. Salvetti, *Underwater manmade and archaeological object detection in optical and acoustic data*, Pattern Recognition and Image Analysis, vol. 24 (2), 310 - 317, Springer, 2014

[12] D. Moroni, M.A. Pascali, M. Reggiannini, O. Salvetti, *Underwaterscene understanding by optical and acoustic data integration*, Pro- ceedings of Meetings on Acoustics POMA, vol. 17, no. 070085, 2013

[13] N. Mittal, D. P. Mital Kap Luk Chan, *Features for texture segmentation using Gabor filters*, Image Processing and its Applications, Conference Publication No. 465 IEE 1999

[14] A. K. Jain, F. Farrokhnia, *Unsupervised texture segmentation using Gabor filters*, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 1990

[15] N. Seo, *ENEE731 Project: Texture Segmentation using Gabor Fil-ters*, Technical report, 2006 http://note.sonots.com/SciSoftware/GaborTextureSegmentation.html