Signal Processing for Underwater Archaeology

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Abstract: About three million wrecks lie scattered on the oceans' seafloors. This huge patrimony is actually threatened by criminal enterprises having advanced tools available for localization and rescue operations. ARROWS, a currently ongoing EU FP7 project, is an example of the effective commitment between cultural institutions and the scientific community towards the safeguard of the sunken cultural heritage. ARROWS is devoted to advanced technologies and tools for mapping, diagnosing, cleaning, and securing underwater and coastal archaeological sites. A fleet of Autonomous Underwater Vehicles (AUVs) will be manufactured with the purpose of surveying the seabed and sensing the underwater environment by means of proper payload sensors (digital cameras, side scan and multi-beam sonars). This paper describes a set of underwater scene understanding procedures specifically tailored to the purposes addressed in the ARROWS frame. In particular the data collected by the AUVs during the acquisition campaigns will be processed to detect targets of interest located on the seabed. The main approach adopted in the object detection procedures is to highlight the amount of regularity in the captured data. This can be pursued by exploiting computer vision algorithms that perform i) the recognition of geometrical curves ii) the classification of seafloor areas by means of textural pattern analysis iii) a large scale map generation to return an overall view of the site and iv) a reliable object recognition process performing the integration of the available multi modal information. Moreover the collected raw data together with the analysis output results will be stored to allow for an offline deep analysis of the archaeological findings. This will represent a powerful tool to be used by expert users or by the general public to enjoy the underwater cultural heritage.

1 INTRODUCTION

The marine environment represents a hostile frame for any kind of human or scientific activity. The peculiar setting imposes strict constraints for survey, mapping and rescue of sunken objects. Given the huge number of wrecks scattered all over the globe's seabed, around three million according to UNESCO reports (http://www.unesco.org/), joint actions between cultural institutions and scientific communities have been fostered by the European Union in order to commit for the safeguard of the sunken cultural heritage.

One of the joint venture aiming at the above cited goals is ARROWS, an EU FP7 project devoted to the development of low cost technologies for marine archaeological site detection and preservation operations. The ARROWS researchers, guided by the suggestions of a dedicated Archaeological Advisory Group (AAG), look for solutions to the mapping, diagnosis and cleaning tasks of underwater archaeological sites. To those particular aims a team of new heterogeneous Autonomous Underwater Vehicles (AUVs) is currently being developed. Those AUVs are designed to host optical (digital cameras) and/or acoustic (Sidescan sonar, Multibeam echo-sounder) payload sensors in order to endow the system with environment sensing capabilities. The captured data will be fed to a scene understanding procedure performing manmade object detection tasks. To this purpose the adopted criteria 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.

Regularity can also be assessed by analysing the objects surface appearance in terms of the repeating textural patterns detected in the captured maps.

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 unstructured area will be marked with low ranks.

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In the first part of this paper the main features of the algorithms implementing the detection and classification tasks will be described. The remaining part of the paper describes the major activity emerging after the project experimental campaigns, concerning the postprocessing of the collected data and the generation of two primary results: i) the 3D models of the detected archaeological objects and ii) a set of large scale maps containing the result of an image mosaicking process, providing an overall view of the surveyed area. These output results are mainly oriented to directly involved cultural operators, enabling them to study in detail every single object without moving it from its environmental framework, but will be also available for dissemination and fruition of the underwater cultural heritage by the general public.

2 AUV SENSING SYSTEM

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. To that aim the underwater vehicles outlined in the previous section will be equipped with a proper set of sensor devices, e.g. optical cameras and acoustic sonars. 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 AUV payload equipment will consist of a couple of digital cameras plus an acoustic device optionally selected between a sidescan sonar or a multibeam echosounder, either forward looking or bathymetric.

3 PAYLOAD DATA PROCESSING

Since the chosen 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 perception 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 column. That represents useless information that has to be erased in order to restore the correct geometrical properties of the data. Intensive fluctuations in the pose of the vehicle which is 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 be reduced by proper restoration and geometry correction techniques the successive goal is to analyse the output data to provide an informative description of the environment.

3.1 Geometry Assessment

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 fulfil the curve detection purposes within the ARROWS project, 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 (Patraucean, 2012), is more thoroughly described in (Moroni, 2013; Moroni, 2014). Some results are showed in Figure 1.

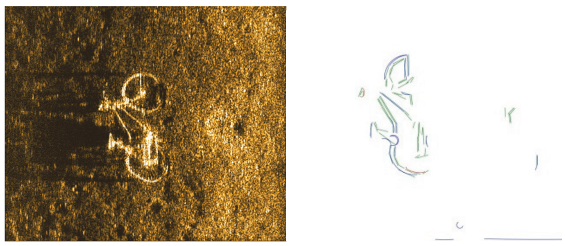

Figure 1: Application of the curve detection algorithm to a side scan sonar image detail (image taken from http://www.jwfishers.com/).

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, 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 components. 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 Figure 2.

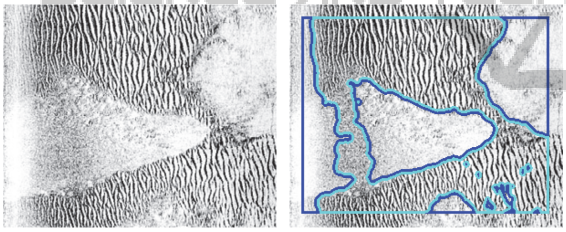

Figure 2: Side scan sonar image segmentation by exploiting of a Gabor filtering technique (image taken from http://www.ise.bc.ca/).

3.3 Seabed Bathymetry

In the ocean's setting the multibeam echosounder is typically exploited for detailed reconstruction of limited areas of the seafloor. The sensor technology is based on the simultaneous collection of echoes from the scattering points located on the seafloor acoustic footprint. During July 2014 a dedicated experimental session has been carried out at the Ocean Systems Lab, Heriot Watt University of Edinburgh. In that circumstance a BlueView MBES 2250 has been employed to survey a small pool facility available in the lab.

The raw output data returned by the MB 2250 consist of 2D maps representing the echo returns collected along the different directions of the acoustic fan (Figure 3). These maps require a pre-processing stage to emphasize and extract the relevant signal from a complex and unstructured background. To this aim the raw acoustic data has

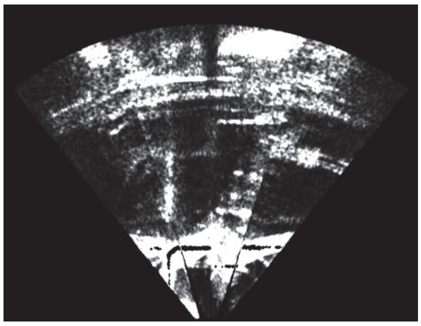

Figure 3: Example of a multibeam echosounder map.

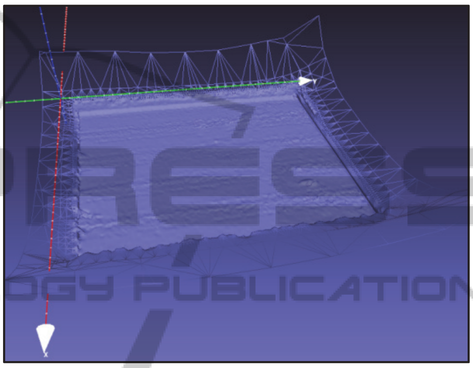

Figure 4: 3D mesh resulting from the processing of the multibeam echosounder maps.

been pre-filtered using a median mask to reduce the corruption associated with the granular noise (Blondel, 2009) affecting the signal.

Later the signal has been manipulated to isolate the connected structure corresponding to the first echoes. To this aim a cascade of morphological transformations (Gonzalez, 2008) have been applied to the map to i) identify the connected components in the map as those structures exhibiting continuity features and ii) to smooth the contour of the objects and to discard undesired protrusions by means of an *opening* operator. Finally the bathymetry has been estimated integrating the pre-processed map and the knowledge of the vehicle position and attitude obtained from auxiliary sensors measuring the vehicle pose. By repeating this operation for every captured map it has been possible to reconstruct the 3D morphology of the pool facility as a set of x, y, z points. The point cloud can be finally refined by generating a mesh (Figure 4).

3.4 Large Scale Maps

In the underwater setting the maximum observable area is inevitably reduced due to the sensor limited performances and to the unfavourable environmental conditions. By exploiting a mosaicking technique (Elibol, 2014; Prados, 2014) the data can be represented in an overall coherent framework, showing clearly the spatial relationship between structures on the seafloor, even if captured at non-consecutive instants.

Figure 5: Image mosaic of the small pool at the Ocean Systems Lab obtained by registering and stitching the captured optical data.

SIFT correspondences can be identified in the overlapping areas of chronologically consecutive maps and exploited to refer all the captured data to a common coordinate system (Lowe, 2004). The following step is to fuse all the data in an overall single synthesis map, consisting of the output mosaic map. An example of mosaicking technique applied to the data captured at the Ocean Systems Lab pool is represented in Figure 5.

3.5 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 synthesis 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. 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 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 Figure 6.

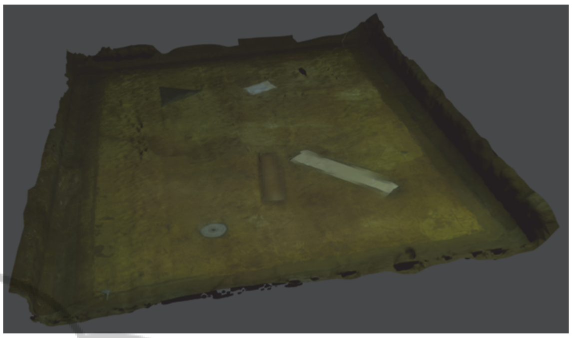

Figure 6: Bathymetric map, obtained by integrating a multi-beam echo-sounder map and an optical mosaic. The data have been captured during an experiment performed in the small pool facility of the Ocean Systems Lab, Heriot Watt University, Edinburgh.

4 CONCLUSIONS

The overall aim of the project is to provide the archaeologist with tools to be exploited in multiple ways. First of all the robotic and automation technology presented in this paper will make easier the archaeologist procedures, carried out in the typical hostile and complex underwater environment. As a byproduct, the archaeologist will be provided with techniques to perform indirect measurements and to formulate an historical interpretation on the findings. Finally, in order to disseminate knowledge regarding the underwater cultural heritage and to increase the sensitivity to the problem of its preservation, the developed tools will be addressed 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 representations. The resulting simulated environment will be populated by the models generated during the project post-processing stage. In the following 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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