1st IMEKO TC-4 International Workshop on
Metrology for Geotechnics
Benevento, Italy, March 17-18, 2016

Opto-acoustic 3D reconstruction of the “Punta Scifo D” shipwreck

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***Abstract* – This paper presents an experimentation, which has been conducted in the underwater archaeological site of Capo Colonna, aimed to verify the joined use of optical and acoustic techniques for the generation of multi-resolution textured 3D models of underwater sites, obtained by merging the results of surveys carried out with these two types of systems.**

I. INTRODUCTION

Underwater Archaeological Parks (UAPs) are a new way to think to the preservation and exploitation of cultural heritage in marine environment. This preservation strategy was started in the last years for two main reasons. First, to promote a sustainable approach on the preservation of archaeological remains and secondly, to exploit the charm exerted by underwater archaeological sites.

Despite their undeniable appeal, UAPs are generally prohibitive for those people that are not familiar with diving, so that their real potential is not actually full-exploited in terms of impact for tourism purposes.

This paper reports the first results of the VISAS project (www.visas-project.eu), cofounded by the Italian Ministry of Education, Universities and Research. This research program is aimed at providing scientific methodologies and technological tools for the virtual exploitation of underwater archaeological sites for people that are not practical in diving operation and to enrich the exploration of UAPs by divers.

One of the main objectives of the project concerns the integration of optical and acoustic techniques for the generation of multi-resolution textured 3D models of underwater sites, obtained by merging the results of surveys carried out with these two types of systems. Such 3D models will be used in an interactive environment for dissemination purposes, giving the possibility to a large audience to explore 3D underwater sites reconstructed in an appealing and realistic way or to support the study of archaeological sites by giving the possibility to navigate in the 3D reconstruction.

Multibeam echosounders (MBES), usually employed for the generation of bathymetric maps in archeological contexts, allow for acquiring a great amount of data at long distances and in presence of bad visibility, but the results are affected by low resolution and do not contain color information. The optical systems, in contrast, are more suited for close-range acquisitions and allow for gathering high-resolution, accurate 3D data and textures, but the results are strongly influenced by the visibility conditions. Therefore, the integration of 3D data captured by these two types of systems is a promising technique in underwater applications, as it allows for modeling large and complex scenes in relatively short time.

Despite the difficulty of combining two modalities that operate at different resolutions, the integration of optical and acoustic systems in an underwater environment has been receiving increasing attention over the past few years, mainly for seabed mapping and egomotion estimation of underwater vehicles [1-4].

Further examples of opto-acoustic integration concern with local area imaging rather than the creation of large area maps. In [5], the integration of video and 3D data, acquired through a single optical camera and a 3D acoustic camera is obtained by geometrically registering such data with respect to a well-known model of the observed scene, while, in [6], the authors propose a new paradigm of opto-acoustic stereo reconstruction that aims to apply the epipolar geometry to a stereo system composed by an optical camera and a 2D sonar.

In this work we propose a method to combine the high resolution 2D and 3D data obtained from photogrammetric techniques with recent advances in the construction of acoustic microbathymetric maps to build three-dimensional representations combining the resolution of optical sensors with the precision of acoustic bathymetric surveying techniques.

In the following sections we present the workflow and the results obtained in a first experimentation of the proposed solution. The test was conducted in the underwater archaeological site located in front of the promontory of Capo Colonna (Croton, Italy) in November 2015.

ISBN: 978-92-990075-0-1

II. ARCHEOLOGICAL CONTEXT

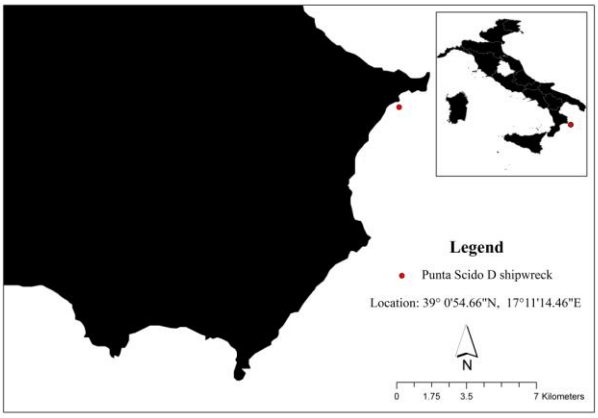

Fig. 1. Geographical localization of the underwater archaeological site near Capo Colonna (Italy).

Capo Colonna is a Magna Graecia archaeological site located in the East coast of Calabria, 10 km from Croton (Southern Italy) (Fig. 1). The site is characterized by the presence of the temple and the sacred area dedicated to Hera Lacinia. Of the ancient temple of Hera, dating from the fifth century BC, only one standing isolated column is left. In ancient times, this area was an important point of reference for many ships on the trade route linking Greece and Asia Minor to Italy, across the Ionian Sea. For this reason, several wrecks of ancient Roman cargo ships (sunk due to adverse weather and sea conditions, or for the presence of reefs) are present on the seabed, in some cases at low depth. Moreover, we can find in this site some significant remains of ports and mining facilities, dating back to the time of Greek domination, submerged as result of the coastal subsidence.

In 1986, in the Punta Scifo bay (at a depth of 7 m), the remains of an ancient Roman cargo ship were discovered and documented [7]. The shipwreck, called "Punta Scifo D", is still in sailing trim and it is represented by an homogeneous cargo of raw or semi-finished marble blocks of considerable size (Fig. 2).

Fig. 2. "Punta Scifo D" shipwreck.

The marble blocks are corroded and concretionated but are cut squared in various dimensions. The vessel is not currently visible on the seafloor, probably because it has been completely destroyed from erosion and/or currents. However, specific study made on the cargo materials [8] have demonstrated that probably it came from the island of Marmara (Turkey) and its dimensions were not less than 40 m in length and 14 m wide.

III. METHOD

Our methodology focuses on the integration of data captured by acoustic and optical systems, in order to obtain a complete representation of the underwater scene and to geo-localize the optical 3D model using the bathymetric map as a reference.

Since the optical and acoustic sensors are based on different physical principles, data alignment, (i.e. their transformation from each sensor's local frame into a common reference frame) is of critical importance for the successful integration of the optical and acoustic 3D models. Indeed, the 3D data generated by these two sensors are very different in terms of resolution and accuracy, so that the alignment made through the recognition of common points in both representations is a complex task.

The main steps of the proposed methodology are illustrated in Fig. 3.

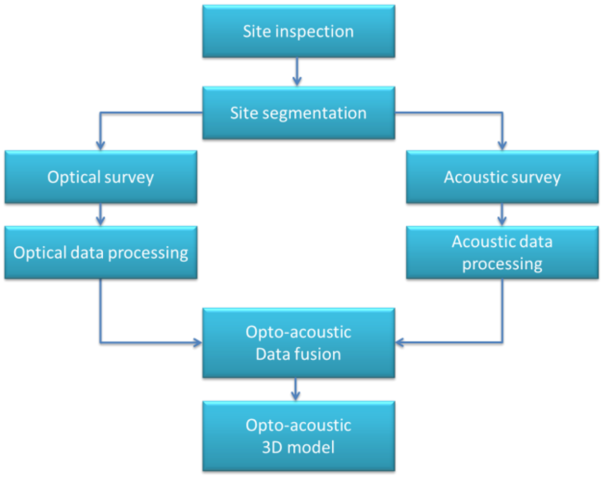

Fig. 3. Processing pipeline of acoustic and optical data.

After a first inspection of the site in order to localize the areas of greatest importance from an archaeological point of view, the integrated survey of the site is realized.

Subsequently, the optical and acoustic data are aligned by using geometrical features correspondences in both acoustic and optical representations. For this purpose, we use the information coming from accurate depth measurements (with errors on positioning < 1cm) obtained employing the high frequency multibeam equipment. Furthermore, to improve the accuracy on positioning, some additional measures are performed by using custom opto-acoustic markers placed on the seabed.

Finally, the opto-acoustic multi-resolution 3D model of the whole underwater archaeological site (the shipwreck and the surrounding seabed in this specific work) will be generated by merging the high-resolution textured 3D model of the shipwreck and mapping the 2D photomosaic of the surrounding area onto the low-resolution polygonal mesh obtained from the acoustic bathymetry.

IV. OPTICAL SURVEY

A. Experimental setup and image acquisition

The camera used to acquire the underwater data is a GoPro Hero 4 silver model, a consumer-brand high definition sport camera with a 12MP HD CMOS sensor, 1/2.5" in size. It uses a fixed-focus lens, which is made with professional-grade glass and has a maximum aperture of f/2.8. The GOPRO Hero 4 records at different video and photo resolutions and Field-Of-View (FOV). In this work, we have used the GOPRO camera (set in video mode) at a resolution of 1080p and a FOV of 108°.

In order to compute the global scale of the 3D model, a set of triangular targets, made of rigid bars of anodized aluminum, each with three markers placed at the vertices of the triangle has been used to perform three measurements, corresponding to the distances between each pair of markers (Fig. 4, left).

Furthermore, to create man-made features in both optical and acoustic representations, we have thought exploit the high reflectivity of the air in water, so we have placed some aluminum rigs covered by bubble wrap in the seabed (Fig. 4, right).

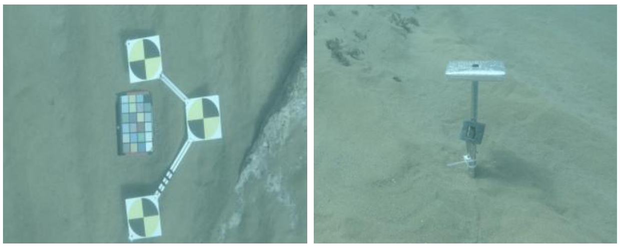

Fig. 4. Triangular target for global scale (left), custom opto-acoustic markers on the seabed (right).

The video has been taken following a standard aerial photography layout (Fig. 5): the diver swims at depth of about 2 meters above the site, acquiring overlapping transects along straight lines that cover the whole area in North-South direction. Another video has been acquired in East-West direction. The occluded areas, not visible in vertical video, have been acquired using oblique poses. Then, the acquired video are been processed in order to extract overlapping frames. The complete dataset includes a total of about 1200 images.

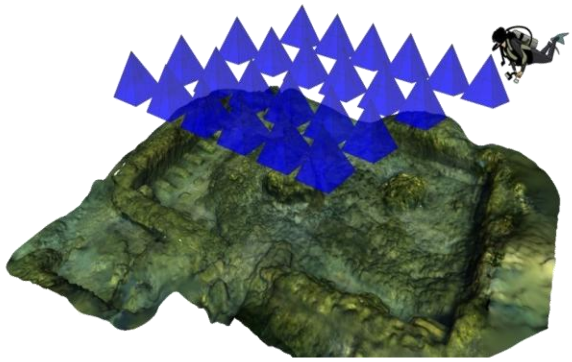

Fig. 5: Image acquisition using a standard aerial photography layout.

B. Image enhancement

The underwater image dataset has been processed in order to reduce the blur due to the scattering effects and to correct the color casts (remove greenish-blue components). In particular, as first step, a sharp filtering has been performed to remove the fog in the images due to the scattering effects. Such an effect reduces image contrast and increases the blur. Secondly, the images are been color corrected by using a new method based on white balancing in the lαβ color space [9]. This method allows to remove the color casts in underwater images by balancing the chromatic components (α and β), while the luminance component (l) is used to improve image contrast by applying an algorithm of cut-off and histogram stretching (Fig. 6).

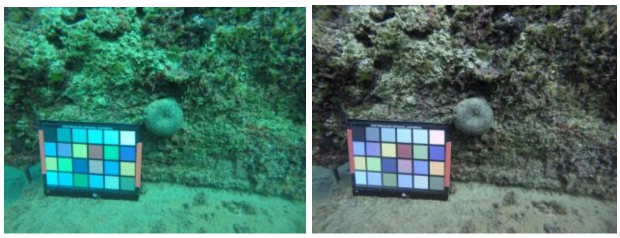

Fig. 6. Sample image before (left) and after (right) image enhancement.

C. 3D reconstruction

For the reconstruction process, the Bundler software [10] has been used to orient the images and to retrieve the camera calibration parameters.

The use of enhanced images has allowed us to orient a subset of 950 pictures covering the whole area. Subsequently, the Bundler's outputs and the undistorted images have been processed with the PMVS2 (Patch-based Multi-View Stereo) algorithm [11]. It estimates the surface orientation while strengthening the local photometric consistency, which is important to obtain accurate models from low textured objects or with images affected by blur due to turbidity in underwater environment. Furthermore, the PMVS2 automatically rejects moving objects, such as fishes and algae.

The output is a dense point cloud (about 12 million points) with RGB information for each 3D point (Fig. 7). Then, the point cloud has been processed with Meshlab in order to select and delete unwanted areas.

The camera orientation procedure has been carried out with an unknown scale factor and it was followed by a scaling of the model, which was carried out by selecting two points with a known distance. In our experimentation, we have used the measures extracted by the triangular target placed on the site.

Fig. 7. Reconstructed 3D dense point cloud of "Punta Scifo D" shipwreck and of the surrounding area.

V. ACOUSTIC SURVEY

A. Multibeam swath bathymetry

Multibeam data were collected by using a Reson Seabat 8125, a 240 beam array with 120° of Swath Coverage and a pulse frequency of 455 KHz. This system is particularly suitable for applications in shallow waters (until 100 m depth) where an ultra-high resolution is required.

The equipment was integrated with a probe for measuring the sound speed through the water column and a motion sensor. During the acquisition, the use of a GPS with differential correction has ensured a sub-metric precision on positioning. This was confirmed by a value less than one for the "precision dilution of positioning" parameter.

All components of the acoustic equipment were managed by using the Quality Integrated Navigation System (QINSy) package, a standard hydrographic software for data acquisition, navigation and processing. In order to provide the best quality as possible and according IHO standards [12], wrong measurements were manually deleted. Erroneous measurements that typically affect records are mainly due to tilted swaths caused by a wrong calibration, an incorrect position due to the GPS "jumps", failure in the heave/pitch/roll/yaw correction of the motion sensor, random false spikes due to poor detection of acoustic beam and to the presence of obstacles along the beam pattern [13]. De-spiked positioning swaths were manually shifted in order to obtain the best fit over the target placed on the seafloor.

B. High resolution bathymetric map

Due to the high resolution needed, the application of the multibeam swath bathymetry technique for the survey of archaeological sites, usually requires longer times for both acquisition and processing steps [14].

The area covered by acoustic data extends about 52.000 m^2 (Fig. 8A) in the -1 m / -14 m below sea level (bsl).

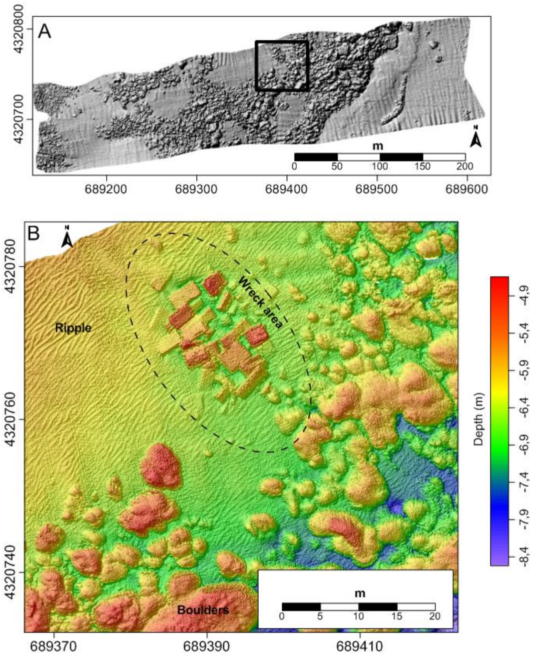

Fig. 8. A) DTM of the area (Grid at 0.1 m). B) DTM of the wreck site (grid at 0.03 m). Ripple shapes from sandy seafloor and boulders can be easily distinguished.

Each depth measurement refers to the center of the acoustic beam that impact the seafloor, thus representing the average depth value of the seafloor sector rather than a spot depth measurement. The dimension of a beam, which is also called footprint, can be expressed with the following equation:

$$Nf = D*tg(SO/NB) \quad (1)$$

where: Nf = Nadir footprint, D = depth, SO = Swath Opening (in degrees), NB = Number of beams in the used array [12].

In our case, the average footprint has been 0.03 m (Fig. 8B), which can be considered the smaller grid cell size in order to build the final Digital Terrain Model (DTM).

The bathymetric map shows a typical shape of sandy seafloor (ripple) and a hummocky surface (Fig. 2B) made up of marble blocks with very different dimensions.

The scattered numb of measurements is shows in Fig. 3A. The wreck area, in particular, extends for 20 x 15 m (Fig. 2B). The marble blocks are partially buried, but some of them outcrop for about 2 m from the seafloor (Fig. 3B). The computation of the residual measurements (i.e. the difference in elevation between the acquired measurements and the grid nodes of DTM) shows that there is a substantial difference between the regularly spaced matrix of the DTM and the scattered numb of measurements (Tab. 1).

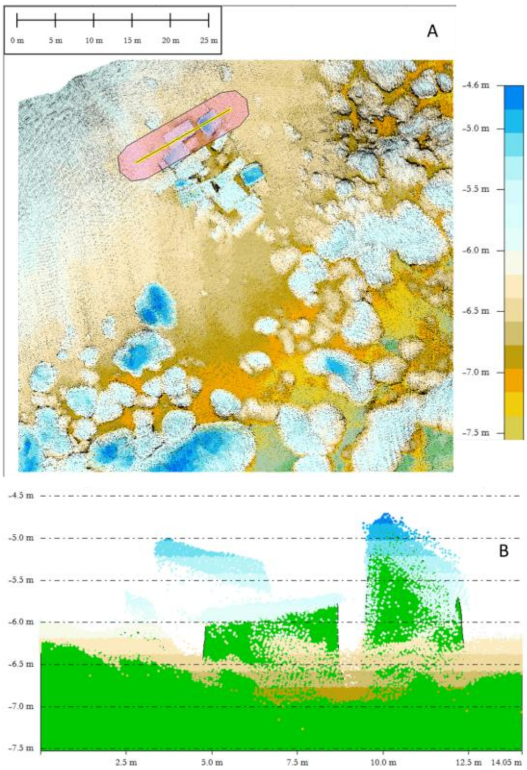

Fig. 9. A) Scattered numb of points of the wreck site. B) Profile extracted (navigation is in A).

Table 1. Statistics of the differences between depth measurements and gridded nodes of the DTM.

Parameter	value
Number of values	1004090
Range	4,225692
Mean	-0,00052
Median	-0,00159
First quartile	-0,03809
Third quartile	0,040378
Standard deviation	0,147075

VI. OPTO-ACOUSTIC 3D RECONSTRUCTION

We proceeded to generate the opto-acoustic 3D model of the shipwreck and the surrounding seabed in this manner. In order to accurately merge the optical data with the acoustic one, the acoustic scattered numb of measurements has been used (Fig. 3A). This solution allows us to avoid the error accuracy on the depth measurements due to the envelope of contiguous cells on the DTM. Equivalently, we have used the optical 3D point cloud for the alignment process.

Subsequently, corresponding points have been manually identified across the two representations. In order to improve the accuracy on positioning, some additional measures have been performed by using the custom opto-acoustic markers placed on the seabed. Finally, the alignment has been refined by using an automatic registration algorithm, i.e. the Iterative Closest Point (ICP). The results are shows in Fig. 10.

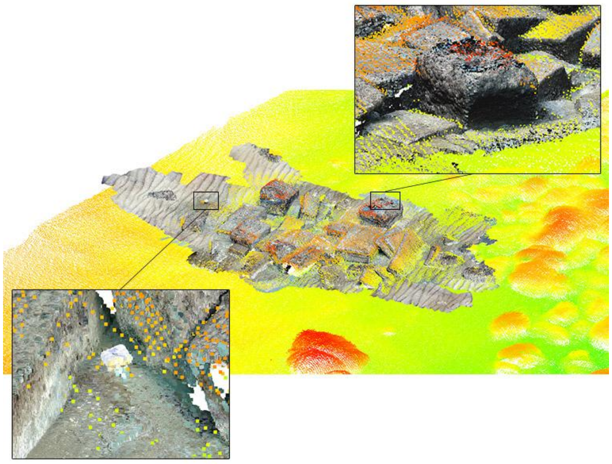

Fig. 10. Opto-acoustic alignment of the “Punta Scifo D” shipwreck and the surrounding seabed.

Qualitatively we can make the following observation. Our methodology for merging the two sensor modalities seems to work well. A visual inspection of the results shows that the individual marble blocks well correspond in the opto-acoustic 3D point cloud.

We have calculated the affine transformation between the two representations in order to define a quantitative error metric and then used the mean distance as accuracy parameter. We have obtained an average error of 15 cm, a good result if compared with those presented in literature [1, 2, 15].

After the alignment step, the opto-acoustic 3D point cloud has been processed with some Meshlab tools. The first operation has been a cleaning and segmentation process in order to obtain a multi-resolution 3D point cloud of the underwater site (Fig. 11).

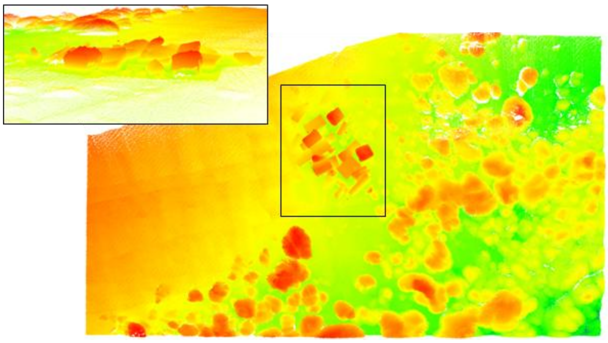

Fig. 11. Multi-resolution 3D point cloud of the "Punta Scifo D" shipwreck and the surrounding seabed.

Then, a watertight surface with about 35 million triangles has been obtained through a Poisson Surface Reconstruction algorithm.

The last step consists in the application of the texture on the 3D surface. Color information can be extracted directly from the colored point cloud, but this method does not allow the creation of an high quality texture, because its resolution depends on the point cloud density.

Since the camera positions are known, the method chosen for texture mapping consists into the projection and blending of the high resolution images directly on the 3D surface. In particular, we have selected an image subset because the averaging among neighborhood values during the blending on the images works better if performed on a largely overlapped area (reducing blur effects). The result of this procedure is a texture with a resolution comparable to the original images (Fig. 12).

II. CONCLUSION

In this paper we have presented a method to combine the high resolution 2D and 3D data obtained from photogrammetric techniques with recent advances in the construction of acoustic microbathymetric maps, in order to build three dimensional representations combining the resolution of optical sensors with the precision of acoustic bathymetric surveying techniques.

We have realized a first experimentation of the method for the opto-acoustic 3D reconstruction of the "Punta Scifo D" shipwreck and the surrounding seabed.

The obtained results show that the joined use of ultra-high resolution multibeam swath bathymetry and photogrammetric techniques is a good solution for obtaining an accurate representation of the whole underwater archeological site.

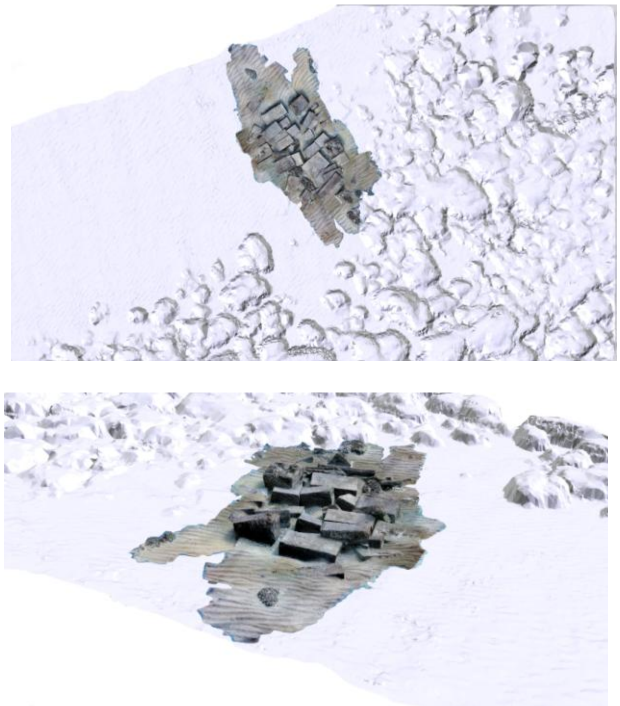

Fig. 12. Multi-resolution (partly) textured 3D model of the "Punta Scifo D" shipwreck and the surrounding seabed.

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