

3D documentation and monitoring of the experimental cleaning operations in the underwater archaeological site of Baia (Italy)

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Abstract— The CoMAS project aims to develop new methodologies and tools for the restoration and conservation of submerged archaeological artefacts. One of the project goals is to study the cleaning operations that are intended to remove the living organisms (algae, sponges, molluscs, etc.). These organisms cause severe deteriorations of the artefacts and their removal is crucial for the subsequent phases of consolidation and protection. In particular, the Unit of Underwater Archaeology of the *Istituto Superiore per la Conservazione ed il Restauro* is experimenting and comparing different cleaning techniques and tools developed in the context of the CoMAS project. This comparison requires also a precise documentation of the test cases and a quantitative measurement of the effectiveness of the cleaning procedures. This paper describes the process that has been defined in order to document and monitor the results obtained through different cleaning experiments, conducted with different tools and utensils over various types of surfaces (marble, bricks, mortar, etc.) affected by several types of biological colonization. The process includes: 1) the 3D mapping of the experimental site; 2) the planning of the tests and the choice of the areas to be cleaned; 3) the 3D reconstruction of the selected areas; 4) the execution of cleaning operations; 5) the 3D acquisition of the cleaned areas; 6) the comparison of the 3D model of the areas before and after the cleaning; 7) the analysis of the data about the cleaning effectiveness. This process has been implemented during an experimentation carried out in the “Villa dei Pisoni”, located within the underwater archaeological site of Baia near Naples.

Keywords— 3D Reconstruction; Underwater; Archaeology; Restoration.

I. INTRODUCTION

The purpose of conservation treatments is to restore the structural and aesthetic integrity of monuments. The tasks to be carried out are cleaning, stabilization, consolidation of the materials and aesthetic finishing.

Following the UNESCO Convention on the Protection of the Underwater Cultural Heritage, the project “Restoring Underwater” was launched in 2001 by the Unit of Underwater Archaeology of the *Istituto Superiore per la Conservazione ed il Restauro* (ISCR). The project is devoted to the study and

experimentation of instruments, materials, methodologies and techniques for the restoration, conservation and *in situ* exhibition of ancient submerged artefacts and structures. It started with the restoration of the *vivaria* of the Roman villa of Torre Astura (Nettuno-Rome), then in 2003 the submerged archaeological site of Baiae (Naples, Italy) [1] became the site of choice for researches. Over the years, many projects were carried out for the restoration of sectors of certain buildings in the protected marine area: the *Villa con ingresso a protiro*, the *Villa dei Pisoni*, the *Via Herculanea*, the *Building with porticoed courtyard* near *Portus Iulius*, and a room of the *thermae* near the *Nymphaeum* of Punta Epitaffio. The project is still on-going and every year the archaeological sites to be restored are selected together with the Superintendence of Archaeological Heritage of Naples and Pompeii, which is currently in charge of the Park. In 2007, 2009 and 2010 three new archaeological sites have been added to the project: a group of nine cast-iron cannons discovered off the coast of the Marettimo Island (Sicily - Italy); the roman wreck carrying a load of sarcophagi discovered off the coast of San Pietro in Bevagna (Taranto - Italy) [2]; the traditional fishing boat recently discovered off the coast of Martana Island (Lake Bolsena - Italy) [3].

The treatment of outdoor and underwater archaeological sites is organized into three progressive levels: first-aid intervention, conservation, and maintenance.

Cleaning operations are needed before proceeding with these treatments: in underwater environment, a gradual mechanical cleaning is the most common solution, starting with the removal of loosely adhering deposits, before proceeding with tightly adhering deposits.

Generally, the instruments used underwater to remove organisms attached to the surface and to cope with calcareous incrustations are brushes and scalpels with interchangeable blades. These biological incrustations, that generally cover the archaeological sites, are responsible for deterioration processes [4, 5, 6]. During the works of the Project “Restoring Underwater” in 2003, an instrument which facilitates the

cleaning activities was designed and tested. It is a pneumatic micro-grinder used to remove the biological incrustations. This tool was realized by making appropriate modifications to a stainless steel drill activated by an air compressor (normally used in orthopaedic surgery). It helps to remove large-sized calcareous or carbon-based incrustations, without damaging the object being restored. The instrument was designed by Roberto Petriaggi, director of ISCR Underwater Archaeology Unit and Project Leader of “Restoring Underwater” from 2001 to 2011.

In 2011 the project CoMAS started and gave the ISCR and the University of Calabria the opportunity to develop more sophisticated tools for the cleaning of underwater archaeological remains and the consolidation of archaeological sites by means of electromechanical instruments. These new devices could make underwater restoration easier and more efficient, but it is important to document and monitor all the experimental phases in order to certify the possible improvements provided by the new cleaning tools.

Moreover, a correct and accurate documentation allows the conservator to follow the evolution of the state of conservation of the archaeological sites over time, and to evaluate the efficiency of maintenance activities on restored sites.

The main goal of this work is to set-up and test a process addressed to document and monitor the cleaning operations by means of multiple 3D acquisition of the areas interested by the restoration. The use of 3D acquisition, in addition to the standard video and photographic documentation, allows us to acquire quantitative measurements about the volume of encrustations removed during the operations or grown over a surface after a certain period of time. In the experimentation presented in this paper, we have tested the process in the *Villa dei Pisoni* within the underwater archaeological site of Baia near Naples, using several tools on various kind of materials (marble, bricks, mortar, etc.) affected by algae and other biological incrustations. In this paper we present the first results of the analysis, currently under development, over two areas that have been cleaned by an electromechanical device.

II. STATE OF THE ART

Underwater archaeology researchers need to survey submerged areas in order to obtain maps and 3D models of finds, artefacts and also entire sites [7], both through optical and acoustic technologies. 3D seismic investigation has recently been carried out, too [8]. Photogrammetric techniques have known an important development during the last decade. Comparison between passive and active techniques have been studied both in air [9] and in water [10] and also the influence of water on calibration procedures has been investigated [11, 12]. Even if good results have been reached using active techniques [13], passive techniques allow for a fast and accurate 3D survey by using a simple and low-cost hardware, also suitable for submerged environments. One of its most important developments is related to the combination with algorithms for Structure From Motion that allow for reconstructing a 3D model of the scene through the application

of photogrammetric techniques on pictures captured from different points of view by a single moving camera; each pose can be estimated thanks to feature-detection algorithms (Scale Invariant Feature Transform – SIFT [14], Speeded-Up Robust Features – SURF [15]).

The increasing effectiveness of multi-view techniques makes them ideal for 3D underwater surveys. In fact, in underwater environment, the acquisition by stereo-systems needs complex hardware configuration and handling. The possibility to use just a simple camera to take pictures, without following an *a priori* defined path, is a great advantage for scuba divers.

Obviously, due to different lighting conditions of underwater environment [16], image-based techniques employed in air could not give satisfying results if the right attention is not paid to avoid and/or correct typical problems of underwater vision (e.g. low contrast, scattering and light absorption and diffusion). Researchers have compared different image enhancement methods [17] and key-point detectors [18] suitable for underwater images. In [19] an automatic, but very slow pre-processing methodology is proposed, intended to detect the best combination of image corrections and feature recognition algorithms. Passive photogrammetry and Structure from Motion (SfM) have been already applied in marine environment for seabed reconstructions, sometimes related to archaeological finds. Some example of seabed reconstruction from a video taken by a camera mounted on a Remotely Operated Vehicle (ROV) are shown in [20] and in [21].

In [22], researchers propose a methodology based on open-source algorithms and software tools to reconstruct the Mazotos area, trying to satisfy different requirements of speed, accuracy, cost and easiness of use for documentation purposes. In [23] an Hellenistic shipwreck consisting mainly of a cargo of amphorae has been surveyed; after having conducted the camera calibration procedure, a photogrammetric technique has been applied on a set of images captured by a scuba diver, which have been corrected and scaled thanks to a previous trilateration adjustment with tape measures; the obtained Digital Surface Model had been used to properly place the 3D theoretical model of the amphora. A similar technique has been previously employed in [24], in which an underwater photogrammetry approach has been used to survey the archaeological site of Pianosa, where the Grand Ribaud Etruscan Wreck lies in deep water [25, 26], in almost impossible conditions for a diver. The digital photogrammetry method employed was based on a non-metric digital camera, mounted in a waterproof housing attached to a bar on a submarine robot. The huge amount of collected data has been used above all for cataloguing and remote visualization purposes. Authors in [27] tested the evolution of methodologies for archaeological surveys on the shipwreck of Dolia in the Tuscan Archipelago, whereas [28] illustrates a project intended to provide methodologies and tools for the mapping, preservation and virtual exploitation of underwater and coastal heritage. In [29] a new type of relief was carried out to document the phases of the restoration of a room paved with opus sectile in the baths of Punta Epitaffio (-5 m) using *Naumacos L1* scanner laser.

Although multi-view techniques have been widely tested with satisfying results in different and challenging conditions [30], we try to highlight and exploit a new possible and interesting aspect related to the use of 3D models; in fact, to the best of our knowledge, this powerful tool has been used above all for surveying and virtual exploitation [31]. In this work, we aim to show how a comparison between 3D models of the same area, surveyed at different times (for example during a cleaning intervention) can provide important information both about the performances of intervention tools and the characteristics and conditions of colonization by flora and fauna.

III. 3D RECONSTRUCTION TECHNIQUE

The 3D reconstruction process starts with the orientation of a sequence of images taken from different viewpoints, using a structure from motion technique. In the first phase, a feature extraction algorithm such as the SIFT is used to extract a set of descriptors across the collection of images to be matched. Subsequently, a bundle adjustment procedure computes the camera positions and retrieves the camera calibration parameters.

In the second phase, a passive multi-view dense stereo matching algorithm identifies some corresponding points across the image sequence. Knowing these correspondences and the scene structure, the 3D world coordinates of each image point can be reconstructed by triangulation. Finding a pair of correspondent points is not so trivial; since the scene is acquired from different points of view, it is possible to find false correspondences due to occlusion, radiometric distortion and perspective distortion.

In passive techniques, artificial lights (lamps and spotlights, for example) are just used to illuminate the scene and are not exploited in the triangulation of the 3D points. Stereo systems use two digital synchronized cameras to capture the scene, which may be installed on underwater robots [32] or used by scuba divers [33].

A preliminary procedure of calibration must be performed to calculate the optical parameters of the camera and to consider the effect of refraction at the air-acrylic and acrylic-water interfaces, which are present when a camera is mounted in its housing. The refraction can be considered through the explicit modelling of the optical paths by using ray tracing [34] or with the implicit incorporation of the refraction effect into camera calibration parameters [35]. In [36] the authors have proposed a method to calibrate an un-calibrated camera for 3D underwater reconstruction of archaeological objects, by integrating the variation of the water optical refractive index with the distortion model.

Open source software (such as PMVS and Bundler) widely used in air for multi-view 3D reconstruction have demonstrated their effectiveness also in underwater applications. In [37] a multi-view technique has been compared with a structured-light technique, without taking into account the optical refraction model. In this work, the multi-view stereo algorithms implemented in Agisoft Photoscan [38] have been used to reconstruct the underwater

scenario, making it possible to orient more than 1500 pictures and to compute the camera calibration parameters of the un-calibrated camera being used.

IV. ARCHAEOLOGICAL CONTEXT

Some explorations and underwater researches conducted in the site of *Punta Epitaffio* and in the Gulf of Baia have identified the ancient site of *Baiae*, which is spread into the sea up to 400 mt. approximately from the coast, whereas 60% of the site is on land. In Roman times, the current gulf was occupied by the *Baianus Lacus*, or *Portus Baiarum* ("Lake" and "Harbour", respectively), as reported by Seneca, Tacitus, Martial, Pliny the Elder and Florus, which later disappeared due to bradyseism [39] (see Fig. 1). The site is recognizable from the ancient ruins located on the banks and the access channel at about -6/8 mt., in the center of the roadstead, cutting the Isthmus that separated it from the sea. To the east of the *nymphaeum* of Claudius (I c. AD, exc. 1981/82) and the stone-paved road toward the foothills (Ist-IVth c. AD, exc. and rest. 2008), there were some *thermae* (Ist-IIIrd c. AD) and a villa dating back to the age of Hadrian (117-138 AD) located south-east of *Punta Epitaffio*, built on the remains of an older villa (late Ist BC-early Ist c. AD), attributed to the *Pisones* thanks to a stamp found on a lead pipe inscription.

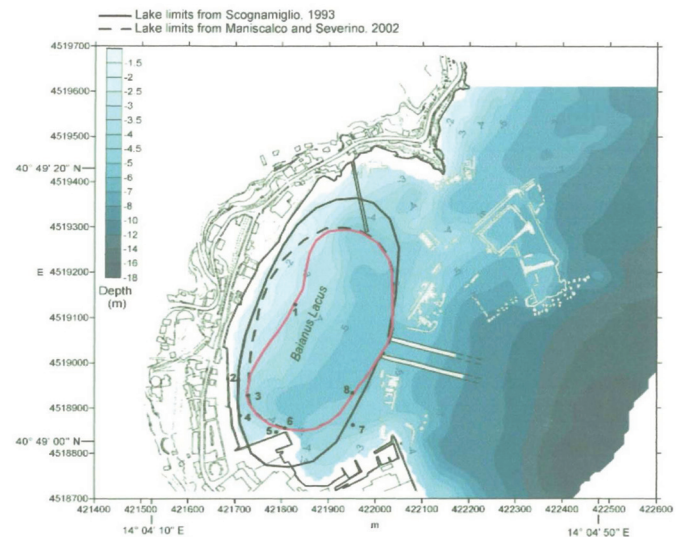


Fig. 1 The *Baianus Lacus*.

The vast complex featured *thermae*, gardens, a maritime quarter - with residential rooms, cisterns, fish ponds and two landing sites - protected by breakwaters, partly similar to *Villa Adriana* (Tivoli), and it has probably been built under the direct intervention of Hadrian. An element of great interest could be a large peristyle, *viridarium*, fish pond or thermal pool (still waiting for archaeological confirmations), like the one found in Bath (UK). Other remains have been found beyond the channel and on the seabed in front of the Castle of Baia.

As it is well known, the ancient submerged remains are subjected to erosion phenomena, man-made damage, and colonization by biological agents. All these factors are

problematic for restoration and preservation, and involve high maintenance costs, as reported during the ISCR experimental restorations (2003-2012) and the P.O.R. of *Baia Sommersa* (2008) [40]; the restored paths are currently in need of maintenance.

V. THE DOCUMENTATION PROCESS

The documentation process, defined to support the experimentation of the cleaning operations, consists in the following phases.

A. 3D mapping of the experimental site

The equipment used to acquire the underwater pictures consists in a Nikon D7000 reflex camera with a 20 mm fixed lens mounted in an underwater housing. Two underwater strobes have been used to acquire pictures of the portion of the site that was characterized by very low lighting conditions. The acquisition has been carried out in a single diving session, in which the scuba diver swam at a certain depth (about 2 meter) following a standard aerial photography layout. The diver followed straight lines with constant speed in North-South and East-West directions, taking more than 1500 pictures with an overlapping rate of with 75% between two consecutive photos. A set of targets with known dimensions and a 4 meters long scale bar have been placed on the seabed in order to scale the model.

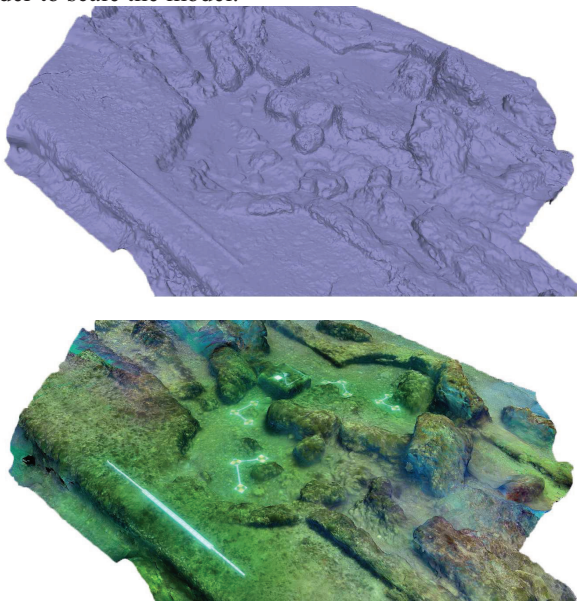


Fig. 2 3D surface and textured model of the site used to plan the cleaning intervention.

A preliminary 3D reconstruction of the whole site has been performed immediately after the diving session. In particular, a set of 1560 pictures, down-sampled to 800x600 pixels to save some computational time, has been processed with the multi-view 3D reconstruction software Phototscan by Agisoft.

Since underwater pictures generally suffer of light absorption, which causes some defects (mostly on the red channel, the

first component of the light spectrum that is absorbed), the images have been pre-processed in order to increase the accuracy of the matching process. In particular, a method based on histogram stretching, shadows/highlights and colour balance has been used.

The processing has been conducted on a workstation based on a CPU Intel core i7, Geforce GTX 680 2Gb and 48 Gb of RAM, and took about 5 hours. The resulting 3D model (Fig. 2) contains about 3.3 million points and 6.5 millions triangles. Since the 3D reconstruction is carried out up to an unknown scale factor, the model has been scaled using the known distances between each couple of target. In particular, the mean value of the measurements has been used to increase the accuracy of the reconstruction, in order to make a 3D map of the site suitable to plan the cleaning operations. The accuracy of the whole 3D model can be estimated through the average error measured on targets that after the scaling process is about 4.5 millimetres.

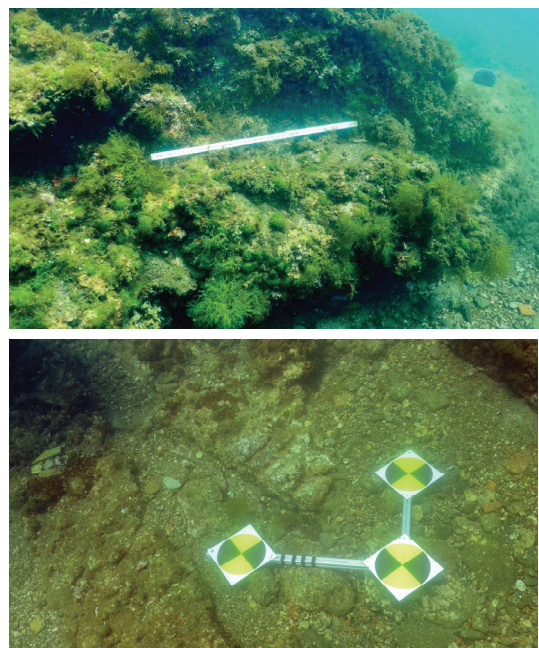


Fig. 3 The two areas selected to test the documentation process.

B. 3D Reconstruction of the selected areas

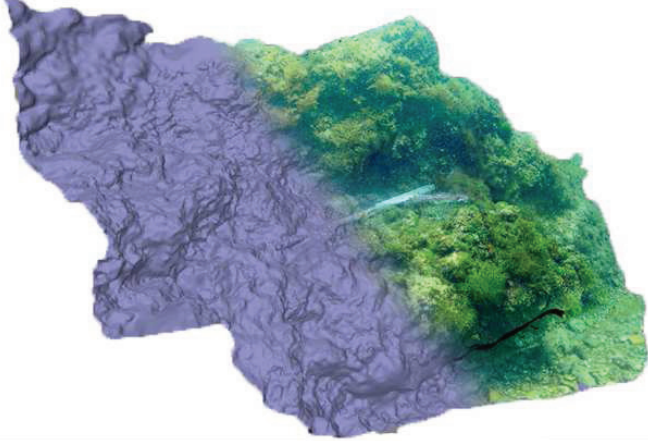
The two selected areas have been acquired at the beginning of the diving session, prior to any cleaning operation. To help the alignment and scaling process, a set of markers and scale bars have been placed on the seabed, surrounding the cleaning intervention area.

About 50 pictures have been acquired for each area, in order to include the surrounding zones to be used as references in the subsequent alignment process between the 3D models, obtained both before and after the cleaning intervention.

The two areas cover a surface of 3 and 1.5 m², respectively, and have been acquired from a distance of about 2 meters.

Despite the presence of marine flora and fauna and the bad visibility conditions, more than 1 million points have been reconstructed for both areas (see Fig. 4 and TABLE 1); in this case the average error drops below 1 millimetre.

Area 1



Area 2

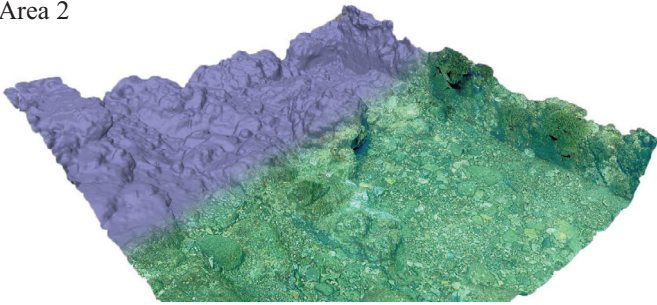


Fig. 4 3D reconstruction (with and without texture) of the uncleaned Area 1 and Area 2.

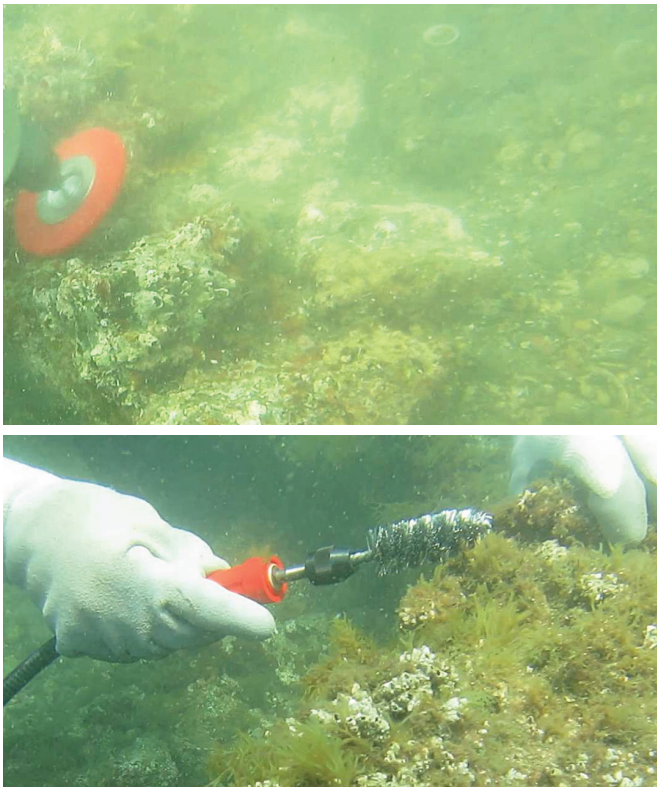


Fig. 5 Cleaning operation performed with nylon and stainless steel brushes.

TABLE 1 RESULTS OF THE 3D RECONSTRUCTION RELATED TO THE CLEANED AND UNCLEANNED AREAS

Area	Images		Points (x 1000)		Triangles (x 1000)	
	Unclean	Clean	Unclean	Clean	Unclean	Clean
1	50	100	1100	1500	2200	3500
2	56	50	1500	3000	2900	6000

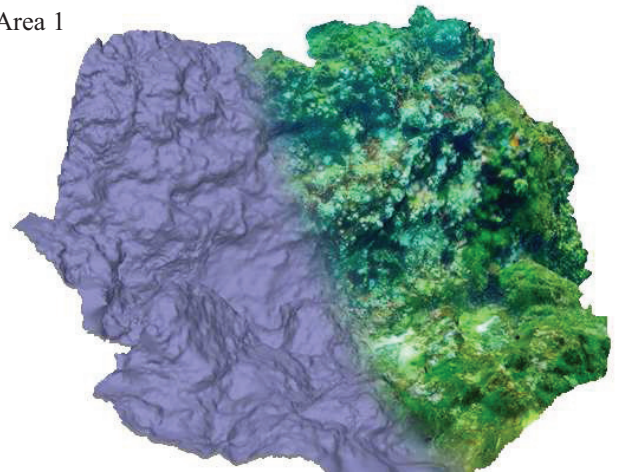
C. Cleaning operations

In this step the selected areas have been cleaned using the devices developed in the CoMAS project equipped with various tools suitable for the different types of encrustation. In particular nylon and stainless steel brushes, of variable shapes and sizes, have been used (Fig. 5).

D. 3D Reconstruction of the cleaned areas

After the cleaning intervention, an additional set of pictures has been acquired for both areas. In particular a sequence of about 100 pictures has been taken for the first area, while about 50 pictures are related to the second one. The pictures have been taken from a distance of about 1 meter, including the surrounding areas as a reference for the alignment process. The results of the 3D reconstruction are summarized in TABLE 1.

Area 1



Area 2

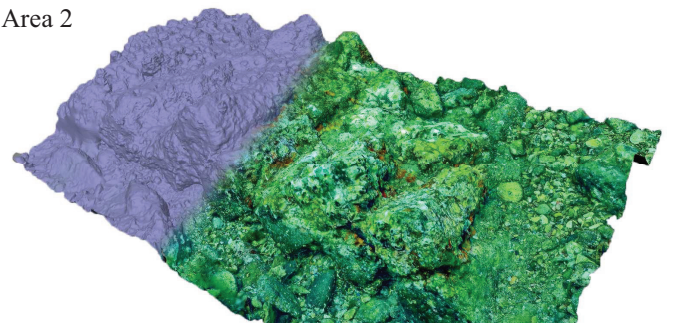


Fig. 6 3D reconstruction (with and without texture) of the cleaned Area 1 and Area 2.

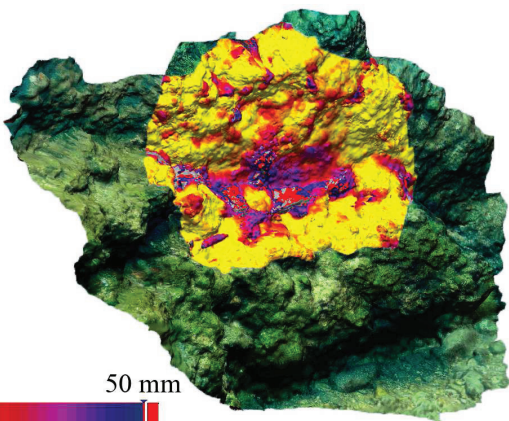
The cleaned surface presents a higher number of points, since the presence of marine organisms that cause problems in the reconstructed surface is highly reduced.

The reconstructed surfaces are shown in Fig. 6. The uncleaned surface presents more defects, due to the presence of algae and other types of bio-fouling, while on the cleaned surface it is possible to distinguish the various types of encrustations that remained on the surface.

E. Results evaluation

The 3D models of both the cleaned and uncleaned surfaces have been aligned in Rapidform [41] by identifying corresponding points in the overlapping areas surrounding the cleaned surface. The use of targets and scale bars was helpful for the alignment process. Once the alignment is done, it is possible to analyse the effect of the cleaning operations on the area of interest by comparing the 3D models obtained before and after the cleaning. Fig. 7 shows the cleaned model, highlighting the misalignment with respect to the uncleaned one: in each particular, the cleaned area is coloured from yellowish to bluish according to its distance from the original surface.

Area 1



Area 2

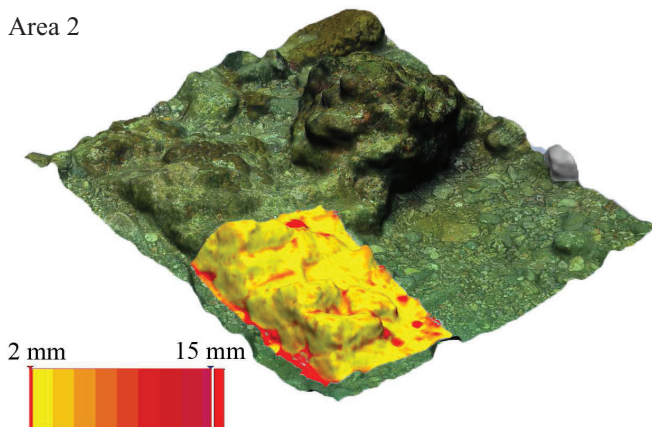


Fig. 7 Mesh deviations obtained comparing the cleaned and uncleaned surfaces.

Different measurements have been conducted on the cleaned areas, summarized in TABLE 2.

The two areas have an extension of 3 and 1.5 m² respectively, and two surfaces of 0.6 and 0.4 m² have been used to perform the measurements. The mean distance is related to the deviation between the reconstructed surfaces before and after the cleaning intervention, while the removed volume has been evaluated by measuring the volume enclosed between the uncleaned and cleaned surfaces, using the mesh processing and analysis tools included in Rapidform.

Additional measurements have been conducted on sections obtained by using different cutting planes. Fig. 8 represents the superposition between the cleaned surface and the initial one, coloured according to the distance; the detailed focuses on possible direct measurements of the removed material. These kinds of information are useful to correlate the amount of removed material with the type of bio-fouling. Higher values have been obtained, for example, on the materials characterized by the presence of algae and plants, lower values are related to the presence of strong encrustation, such as *Thoracica*.

TABLE 2 RESULTS OF THE ANALYSIS CONDUCTED COMPARING THE UNCLEANNED AND CLEANED SURFACES.

	Area 1	Area 2
Selected area (m ²)	3	1.5
Analysed area (m ²)	0.6	0.4
Mean distance (mm)	9	3.6
Max distance (mm)	47	12
Removed volume (dm ³)	5.4	1.5

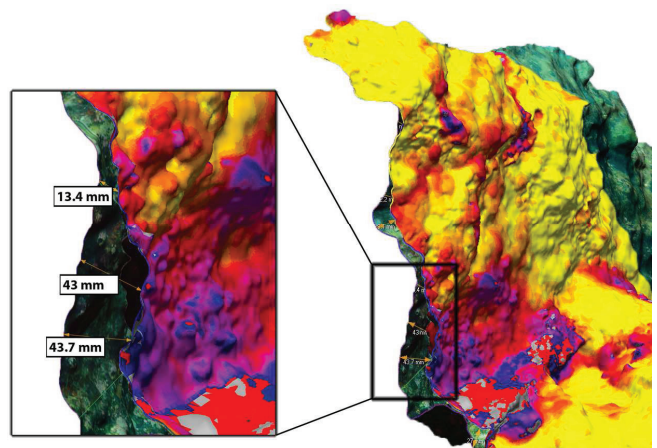


Fig. 8 Cross-section analysis used to correlate the amount of removed material with the type of encrustation.

VI. CONCLUSIONS

The documentation process presented in this paper aims to produce quantitative data about the effectiveness and the

efficiency of the new cleaning devices which are currently under development in the CoMAS project.

The experimentation has been conducted on various areas characterized by the presence of different materials (marble, bricks, mortar, etc.) affected by various types of biological colonization.

For each area, multiple tools have been experimented and the operations have been documented by photos, videos and 3D reconstructions. The first results, reported in this paper, were collected in only two of the areas interested by the cleaning operations, but they demonstrate that multiple 3D reconstructions, acquired during the different steps of the operations, can be used to improve the documentation process with quantitative data about the volume and the mean and max heights of the removed incrustation. The encouraging results obtained in this experimentation will be tested with *ad-hoc* specimen and compared with other measurement and reconstruction methodologies employed in underwater environment. This will better motivate the decision to extensively use this process in the experimentation of the cleaning operations, which is currently on-going. This process will allow us to compare the results obtained in different operating conditions, and it could be decisive in driving the future development of cleaning device prototypes. Moreover, we intend to experiment this process for monitoring purposes; in fact we would like to acquire some of the cleaned areas at regular time intervals, in order to monitor the colonization process.

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