Underwater photogrammetry for archaeology and marine biology

40 years of experience in Marseille, France

Abstract— Since 1973 archeology and computer science have developed close ties in Marseille. Two departments (computer science and archaeology) from the French National Centre for Scientific Research (CNRS) in Marseille started working together and laid the cornerstone of the Computer Applications and Quantitative Methods in Archaeology (CAA) community. Marseille also has the advantage of being located in a very interesting place on the Mediterranean Sea and being the home to several famous laboratories, such as the French Cultural Heritage Department (DRASSM) or private companies like COMEX.

In 1980 they performed a series of explorations of a deep-sea wreck with the help of COMEX and DRASSM. More recently, ten years ago, the Centre d'Océanologie de Marseille (COM) started using underwater photogrammetry to survey and monitor red coral populations *in situ*.

In this paper we present new advances in underwater photogrammetry for archaeology and marine biology based on forty years of experience. The survey described in this article does not only discuss the acquisition of 3D points in difficult conditions but also linking archaeological knowledge to the surveyed geometry. This approach needed to combine automatic data processing and offered the opportunity to experts, archaeologists or biologists, to insert knowledge in the process.

After an introduction to the history of computer science and archaeology, we will present related work in underwater archaeology and marine biology. The last section is dedicated to two recent experiments in Marseille, based on recent developments in automatic photogrammetry: a World War II plane wreck, surveyed using both acoustic and optical sensors, and a survey used to monitor red coral growth over several years.

Index Terms—Archaeology, marine biology, *Corallium rubrum*, benthic communities, underwater, photogrammetry.

I. Introduction

Archaeological excavations are often irreversibly destructive, so it is important to accompany them with detailed documentation reflecting the accumulated knowledge of the excavation site. This documentation is usually iconographic and textual. Graphical representations of archaeological sites such as drawings, sketches, watercolors, photographs, topography, and photogrammetry are indispensable for such documentation and are an intrinsic part of an archaeological survey. However, as pointed out by Olivier Buchsenschutz in the introduction to the symposium *Images and archaeological surveys*, in Arles, France, in 2007 [1, Introduction page 5], even a very accurate drawing only retains certain observations that support a demonstration, just as a speech retains only some arguments, but this choice is not usually explicit. This somewhat lays the foundation of this work: a survey is both a metrics document and an interpretation of the site by archaeologists.

The survey is a very important component of this documentation and its importance is largely due to the fact that the concepts employed by archaeologists during an excavation are closely related to space. The structure of the excavation is based on the concept of stratigraphic units. Inherited from geology and then formalized for archaeology by E.-C. Harris [2], stratigraphic units are linked by geometric, topological and temporal relationships. They are fundamental for the interpretation of the archaeological excavation.

Two families of objects have to be surveyed: first, the artifact that we seek to position in space and of which we have a good a priori knowledge; and second, the area being excavated (in this case, a part of the seabed), often represented as a digital terrain model (DTM). Throughout this work we deal with these two aspects, artifacts and unstructured land, by addressing two different approaches; one using a priori knowledge through measurements and the second based solely on geometry.

The first approach, based on the a priori knowledge that we have about the measured artifact, uses our knowledge of the object to compute its size and position in space. This method can also reduce the time required for measurements. The second approach, used to survey land for example, uses automatic tools coming from photogrammetry to compute a dense cloud of 3D points.

Finally, a very important point is the link between geometry and knowledge; a model, 3D or 2D, representing a site is a relevant interface to access the data known about the site. 3D representations of a site provide important added value to underwater archaeologists who are then able to study a three-dimensional overall picture, which is otherwise difficult to obtain in underwater environments. This offers a significant advantage in the creation of new assumptions regarding the reconstitution of the shipload or vessel itself [3, 4].

Moreover, it should be noted that, by nature, archaeological data are incomplete, heterogeneous, discontinuous and subject to possible updates and revisions. The documentation system, linked to archaeological data, must be able to manage these constraints.

II. 40 YEARS OF EXPERIENCE IN MARSEILLE

A. Computer science and archaeology

Since their development, computers have been used by archeologists. At the very beginning, this new tool was used to store (databases remain a key element for archeology), sort and statistically analyze large amounts of data. As early as 1955, Jean-Claude Gardin developed a mechanographical documentation system for archeology [5]. Beyond this approach, computers were used very quickly for relative temporal ordering, classification, and artificial intelligence, with, for example, the wide-spread use of expert systems in the 1980s, then for visualization, measurements (photogrammetry and laser scanning), and today, for virtual reality.

At the beginning of the 1970s, the links between archeology and computer science in the field of artificial intelligence and classification were already highly developed in the scientific communities around Marseille. The archeologist Robert Whallon, professor at the University of Michigan, wrote the following in 1972 in article entitled "The Computer in Archaeology: A Critical Survey" [6]:

"*The growing concern in archaeology with the new methods made possible by computers is reflected in the increasing size, frequency, and importance of the sessions on analytical and statistical methods at professional meetings. Indeed, each of the three years that have passed since Chenball's review article in this journal, a special meeting has been held, devoted only to such problems:*

1969 - Marseille: International Symposium on the Application of Computers in Archaeology [7].

1970 - Mamaia: Anglo-Romanian Conference on Mathematics in the Archaeological and Historical Science [8].

1971-Marseille: Seminar on the Mathematical Methods of Archaeology (from the press).

A shift away from concern with the computer per se toward greater interest in methods of analysis can be seen in the changing titles of these conferences."

These links between archeology and computers from then on became deeper and very quickly materialized with the creation of the international *Computer Applications and Quantitative Methods in Archaeology* (CAA) organization (http://www.leidenuniv.nl/caa/about_caa.htm) which groups together archeologists, mathematicians and computer scientists in order to encourage and support exchanges between these fields of science. Since 1973 an annual conference is held to summarize members' activities.

B. Classification and artificial intelligence in archeology

The 1972 conference in Marseille [7] followed by the creation of the CAA were the first signs of the emerging quantitative methods in archeology and especially their mathematical formalization due to truly interdisciplinary work. The first well-known advances were related to the formalization of archeological data and followed by the management of this data. It was classification that was the common thread of the first applications of these databases. [9-15].

The systematic processing and backing-up of this great amount of data opened new doors for archeology. Above and beyond principal component analysis (PCA) and other statistical *clustering* techniques [16, 17], Doran suggested a knowledge-based approach as did Jean-Claude Gardin during the same years.

The 1980s led a real boom in the use of expert or knowledge-based systems in archeology. [18, 19]. One can highlight, for example, the work of Juan Barceló [20] or Vanda Vitali [21] in dealing with classification and ceramic applications, which were in a way the extension of the efforts made in the 70s for classification and the beginnings of a more intensive use of artificial intelligence in archeology, a use which is still evolving today.

After an intensive period in the 1980s and 90s [20, 22-25] where knowledge-based systems were heavily used in archeology, it should be remembered that the latest developments in spatial reasoning, for example, are having a hard time being used in the human sciences.

Beyond the limits of expert systems, whose results are not miraculous even if they were promising for those living at the end of the 20th century, the appearance of 2D and 3D graphic management applications as well as 3D optical measurement tools (laser scanner, digital photogrammetry, virtual reality) have been a major force of attraction for archeology. Offering immediate and visible results, a considerable effort was made for the use of virtual reality linked, or not, with automatic measuring means.

C. The beginning of underwater photogrammetry in archaeology

The invention of the pressure regulator (Aqua-Lung) in the 1950s enabled scuba divers to reach underwater archaeological sites and gave them the possibility of studying the wrecks of sunken ships. After the first experiments in the Fifties (of which the "excavation" of the *Grand Congloué* by Jacques-Yves Cousteau and Fernand Benoit represents a milestone; celebrated, but unfit from the scientific point of view), archaeologists in the Sixties understood that they had to dive themselves to ensure that the terrestrial scientific methods used for underwater sites were correctly applied. The terrestrial methods of excavation, based on principles coming from geology and prehistoric archaeology (stratigraphic excavations), were applied by using tools adapted to the sea environment, such as suction dredgers powered by air or water, in order to remove sediment without moving the objects constituting the load of a wreck, and by excavating layer by layer the hull of the ship. On the other hand, the methods of terrestrial graphic statements (horizontal planes, vertical cuts) could not be adapted in a simple manner as they were based on optical tools, theodolites, levels, etc. Traditional methods such as tracing right angles or placing test cards on a horizontal plane were possible, but the manual graphic statement was not adaptable to the excavation of an important cargo of amphorae, ending up to be much too slow and vague without the use of a theodolite.

The first experiments of underwater photogrammetry for archaeology began in the Sixties [26]. In the same decade, the Naval Oceanographic Office in Washington performed the first experiment with underwater photogrammetry on a submarine under the direction of Joseph Pollio [27]. Afterwards, other experiments took place involving the basic concepts that we use today [28, 29] [30]. Since then, the interest in photogrammetry and acoustic measurements for archaeology has continued to grow [31, 32].

In 1964, the submarine Asherah, with financial support from the National Geographic Society, was inaugurated in Turkey, and by 35 m deep took the first-ever stereoscopic photographs of the Yassi Ada 2 Byzantine wreck (Bass, 1970; Bass & Rosencrantz, 1973). A large mechanism was needed to achieve these stereoscopic images. With the experiences gained in 1972 from the Roman wreck of the Madrague de Giens, one of the first photogrammetric surveys of a shipwreck in France was performed in Marseille by the French archaeologist J.-C. Négrel [33, 34]. While two synchronized cameras were taken on board the submarine Asherah, the divers in Marseille surveyed the site using fixed and sliding metal structures. Indeed, in 1972, this heavy framework was used on two Roman shipwrecks: Pointe de la Luque A and B, near the Pomègues island, successively by 20 and 40 m of depth, to guide the cameras shooting the stereoscopic images. Photogrammetry was essentially used, in both cases, for the study of the hull of ships. It was subject to strong geometric constraints; images were to be made in accordance with human physiological conditions required for stereo vision: parallel optical axes and no tipping (rotation around the optical axis). But, in 1984, in the very same waters in Marseille near Carry-le-Rouet, other French submarine archaeologists were able to use lighter tools, in particular on an ancient shipwreck loaded with limestone blocks by 5 m deep [35]. This Greek ship transported blocks for the construction of the ramparts of the city of Massalia. To avoid having to use heavy supports and the usual cumbersome frames, two piano strings pulled taut parallel to the longitudinal axis of the site, and leveled, were used as a basis mark for the taking of pictures. Moving along these strings, a metallic graduated triangle gave a metrical scale while index-marks with reference-points indicated the vertical one. A photographic support fitted with two Nikonos cameras (28 mm) in 1984, and two Hässelbläd cameras (50 mm corrected) in 1985, was connected by a nylon thread to this graduated triangle. These two camera supports (the first one made of plastic and the latter made of aluminum) have a positive buoyancy and provided perfect stability thanks to their opposing forces. This method happened to be speedy, inexpensive, and efficient. The fittings of strings and the general film-shooting, as a matter of fact, needed less than two hours. The three-dimensional plan of the cargo was made by a stereo-plotting company (SETP, Salon-de-Provence, France), from pairs of pictures, by means of an analytic stereoplotter called a "Traster" manufactured by the Matra-Optique firm.

After these first experiments, numerous other missions of simplified photogrammetry were performed by the DRASSM on deep-sea shipwrecks. As in Turkey with the Ashera, most of them used submarines floating above the archaeological remains. Then, similar operations were carried out, again all around Marseille, for instance in the Cosquer cave in 1994, and then on the Roman shipwreck Sud-Caveaux 1, by 65 m deep. In the Cosquer cave, a submerged prehistoric site by 37 m deep, the problem was different because only the entrance and a long access corridor were underwater. There, two systems were used together, the Soisic laser sensor, developed by EDF, and the inevitable photogrammetry, used in addition, as an exhaustive way to record the geological forms of the cavity and to capture the anthropological traces.

In 1996, on the Sud-Caveaux 1 wreck, thanks to logistics provided by COMEX, the photogrammetric survey took place using the Remora 2000 submarine and a ROV Super Achille (COMEX), to obtain a three-dimensional representation of the remains preserved at the surface of the seabed. A metric chamber (Sapho-COMEX) calibrated on a micrometer scale was moved at constant height and regular speed above the shipwreck. Beforehand, both submersible machines had put index-marks and graduated rulers around the tumulus of amphorae for the photo calibration [36].

Similar operations continued more recently, still in waters close to Marseille, for example during the fusioning of optical and acoustic data on the ancient site of the bay of Catalans, in Marseille [37]; but also on the Roman deep-sea wreck, the Pointe de la Voile, by 100 m deep, and in 2009 on the impressive cargo of amphorae from the shipwreck Port-Miou C, by 105 m deep, within the framework of the European project, Venus. So, it is clear that the seabed in the region of Marseille and the groups of different researchers always favorably lent itself to the virtual exploration of underwater archaeological sites.

III. Underwater photogrammetry

A. Operative considerations

The principle of underwater photogrammetry does not differ from that of terrestrial or aerial photogrammetry, but it is necessary to take into account certain elements that may cause disturbances; in particular, the refraction of the diopter water-glass and the presence of the camera housing [38].

The specific constraints of the underwater medium (turbidity of water, presence of suspended particles) force the operators to work on a large scale, close to the objects (between 0.5 and 2 to 3 meters, depending on the water quality). This apparently constraining aspect imposes having to produce a great quantity of stereo pairs, but on the other hand it offers a very high degree of accuracy.

The important advantage of using photogrammetry in underwater surveys in comparison with the use of other techniques consists in its simplicity of implementation and the diversity of potential results (3D measurements on the object, 3D reconstruction, orthophotography, and vector restitution).

The implementation only requires the use of a scale bar to compute the scale of the model. Moreover, if two or three synchronized cameras are used, additional equipment is not needed at the scene as the scale is computed using the calibration of the camera set. This approach also provides a relevant appreciation of the uncertainty of measurements; where, in addition, the photographs have to be taken with an important overlap. The key factor of this method is redundancy: each point of measured space must be seen in at least three photographs.

The operative advantage is related to the simplicity of the survey. Moreover, a submarine pilot can drive a remotely operated underwater vehicle (ROV) without having to undergo a long preliminary training period. This method requires little time and does not require specific personnel, thus greatly reducing the expenses in a context where time and costs of intervention are extremely high.

B. Automatic photogrammetry survey

The photogrammetric process is a very efficient procedure consisting mainly of three phases. The first phase is data acquisition by photographs which requires light processing, is non-intrusive (remote sensing), only slightly time-consuming (only the time necessary to take pictures), and potentially a quite thorough practice. The second phase involves further data processing and is carried out in a laboratory. This phase, which is mainly automated, includes homologous point determination and photo exposure estimation. The last phase, data interpretation and linking with domain knowledge (archaeology or marine biology) is always manual, performed by experts and very time-consuming.

By using an ROV equipped with cameras, it is possible to minimize the time and costs of photo elaboration, taking advantage of the way underwater photographs are taken (often by strip with an overlap from one photo to the next).

Using the SIFT [39, 40] algorithm to detect homologous points, and now the FAST descriptor algorithm [41], we are able to make all the possible relative orientations using the Stewenius algorithm [42-44].

All the photos in a same reference system (up to 20 photos) can be correctly oriented using a technique developed by LSIS laboratory. In the same way, we have implemented in Java code the Furukawa algorithm for cloud point densification, with some small modifications in order to fit better our case. For a large quantity of photographs, we use the C++ implementation of the open source software by Manolis Lourakis [45] and Noah Snavely [46] for the *Bundler* software and finally Ponce and Furukawa surface densification software for point cloud generation [47, 48].

This software suite is now open source and freely available on the Internet.

An interesting application is being developed by the IGN in France and offers dense 3D motion capture software which is also open source [49]. Their approach is more rigorous from a photogrammetric point of view and allows using calibrated cameras.

C. Underwater 3D survey merging optic and acoustic sensors

Optic and acoustic data fusion is an extremely promising technique for mapping underwater objects that has been receiving increasing attention over the past few years [50]. Generally, bathymetry obtained using underwater sonar is performed at a certain distance from the measured object (generally the seabed) and the obtained cloud point density is rather low in comparison with the one obtained by optical means.

Since photogrammetry requires working on a large scale, it therefore makes it possible to obtain dense 3D models. The merging of photogrammetric and acoustic models is similar to the fusion of data gathered by a terrestrial laser and photogrammetry. The fusion of optical and acoustic data involves the fusion of 3D models of very different densities – a task which requires specific precautions [51, 52].

Only a few laboratories worldwide have produced groundbreaking work on optical/acoustic data fusion in an underwater environment. See for example [53] and [54] where the authors describe the use of techniques that allow the overlaying of photo mosaics on bathymetric 3D digital terrain maps [55]. In this case we have important qualitative information coming from photos, but the geometric definition of the digital terrain map comes from sonar measurements.

Optical and acoustic surveys can also be merged using structured light and high frequency sonar as by Chris Roman and his team [56]. This approach is very robust and accurate in low visibility conditions but does not carry over qualitative information.

IV. An Experiment on the Junker 88, Marseille

The complete workflow, from taking photographs on site to 3D point visualization and measurements, including photo orientation, cloud point generation, merging with acoustic survey and finally densification, was experimented on a World War II plane wreck, the Junker 88, discovered close to Marseille in 1989 by 53 meters deep.

A. One day on site

The photographs were taken in a single day and only one dive from the COMEX Remora 2000 submarine. A Nikon D700 and two strobes where used to take 1500 photographs. One survey was taken 3 meters from the object and another one at a distance of 80cm.

The same day, a survey using an acoustic sensor and a 3D camera from BlueView was made and was then used to scale the photogrammetric model.

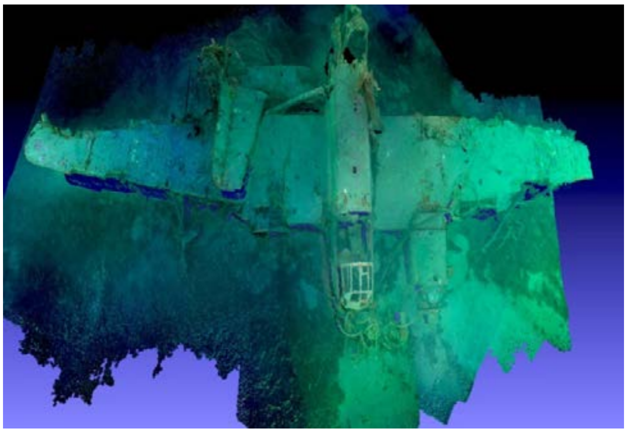

Figure 1. Overview of the wreck with the cloud of 3D points. 25 million points computed on 1330 photographs. Model scaled on SONAR survey. 3D point visualization in PLY format by Meshlab.

Figure 2. One of the photographs taken from the ROV with a high definition digital camera (Nikon D700 lit by two strobes). This allows for a high definition 3D model and very good digital documentation.

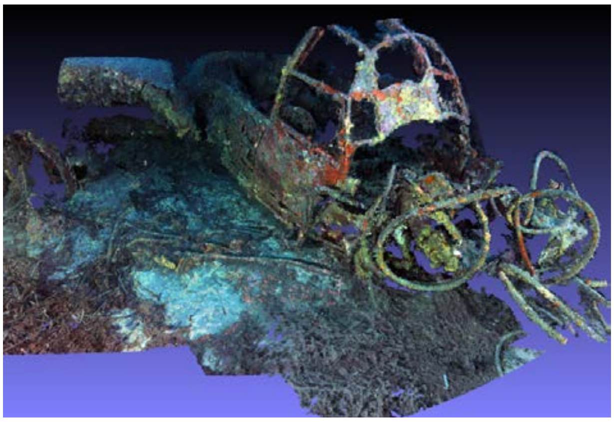

Figure 3. High definition 3D model, detail. Scaled on acoustic survey, accuracy 5mm.

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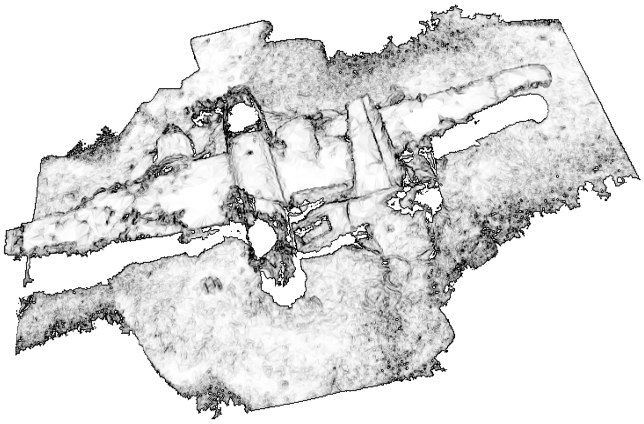

Figure 4. 3D model visualization with the Arpenteur 3D tool. Fluent navigation with millions of points, merging camera and photo used for measurement and interaction with expert. Shown here an on-line shader for Non-Photorealistic Rendering.

B. Conclusions

This one day mission on the Junker in Marseille was done to demonstrate that it is now possible, in a short time, to acquire a good set of photographs using standard equipment (Nikon D700 and two Nikon SB800 strobes). The photographs can be used as a good support for documentation as well as processed by photogrammetry with open source software. The final scale and reference system fits with an acoustic survey done with the BlueView 3D camera in order to be aware of possible drifting resulting from the processing of a huge quantity of photographs by bundle adjustment. Two days were necessary to process the photogrammetric data and to merge with the acoustic one. We are currently working on two problems dealing with this kind of survey: a more accurate and automated way to merge photogrammetry and SONAR data considering the difference of the two results (resolution, accuracy, surface of survey) and a way to automatically compensate for water turbidity [57, 58].

V. Underwater photogrammetry for marine biology

A. 10 years of experience

The Mediterranean red coral, *Corallium rubrum,* (Linnaeus, 1758) is a slow-growing coral which can reach 50 cm in height and live for up to 100 years [59, 60]. The red coral is found mainly in the Mediterranean Sea and forms dense populations in dim-light habitats at depths between 10 and 600 m. Its red calcareous skeleton has been appreciated for its use in jewelry since ancient times. In fact, over-harvesting red coral caused a dramatic change in the size of the coral skeleton and now most populations are dominated by small-sized colonies (< 10 cm in height and 5 mm in diameter). Moreover, red coral is also suffering from the effects of climate warming which can severely increase mortality rates. Finally, scuba divers often unintentionally damage red coral colonies with their gear, making it harder for the coral to recover from other disturbances. Monitoring the current state of red coral populations is a basic step in designing sound management and conservation plans for this threatened species. *In situ* surveys in red coral populations are difficult since they usually develop in deep water (>20 m depth) limiting the diving time and in semi-dark habitats (overhangs, cave entrances, vertical walls). In addition, red coral are fragile, rending difficult the application of direct measurements as is currently done for other benthic species.

B. Long term study

Underwater photogrammetry was chosen to survey red coral populations because it is able to quantify the size-structure of populations with a high precision and limits direct contact with red coral colonies. Also, the setting up of permanent plots offered the opportunity to follow the fates of surveyed colonies including the assessment of growth rates by comparing colony sizes through time. Bearing in mind that red coral is a very slow growing species (e.g. ~ 0.20 mm per year in diameter) and the precision that underwater photogrammetry can offer, we contend that this method is able to furnish good growth rate measurements.

To carry out the surveys, we set up permanent plots in different locations of the NW Mediterranean Sea. The sites were located in both protected (dwelling within marine nature reserves) and harvested populations. The plots were set up using PVC screws attached to holes in the rocky substratum. Each plot was variable in length, depending on the complexity of the substratum, and 40 cm wide. The total area covered in each site was about 2 m^2. Transects were photographed using different reflex cameras equipped with a housing and two electronic strobes. In each sampling, a cord was deployed between the screws to help define 20x20 cm quadrats sequentially positioned along the cord (above and below the cord length). At each position, two photographs from each quadrat (using two slightly different angles, approximately 30°) were taken. The quadrat was used as a scale reference and, over the past few years, we also attached tags to help in the automatic orientation and scaling process.

Permanent plots were photographed on an annual basis. For some sites we have already gathered 10 years of surveys. From the photographic series, we can estimate the basal diameter, the maximum height and the number of branches of each colony found within the permanent plot. In addition, we can calculate the density of colonies, the necrosis rate, the breakage of branches and the presence of signs of recent harvesting.

C. Some results of the red coral populations surveys.

Underwater photography has been used to monitor 10 populations in the NW Mediterranean Sea. Permanent plots have been set up in in 5 marine nature reserves (Parc Natural del Montgrí, les Illes Medes i el Baix Ter, Réserve Naturelle Marine de Cerbère-Banyuls, Parc Marin de la Côte Bleue, Parc National de Calanques et Réserve Naturelle de Scandola). Except for the populations within the Parc National de Calanques near Marseille which was created in 2012, coral populations benefit from protective measures for the last few decades. The analysis of photographic surveys allowed to obtain the following main results: (i) data on size-structure of populations submitted to different protection regulations which provided helpful information for the evaluation of the effectiveness of management measures on coral populations; the conservation status was higher in marine protected areas where all kinds of human activities are prohibited except scientific surveys (Linares et al. 2010). (ii) The comparison of colony sizes monitored annually from permanent plots allowed to obtain reliable growth rates in height (Garrabou et al. unpublished data). (iii) Quantify the impact and recovery of harvesting events in unprotected populations in the Marseille area. In fact, fishermen often leave basal parts of the colonies from which red coral could recover. The photogrammetric analysis allowed quantifying the rates of recovery which resulted in a relevant mechanism to explain the persistence of populations subject to harvesting [61].

The coral are manually measured by the biologist and a real-time check consistency control is performed according to statistical analysis on the item already measured and a high definition densification process in order to define a possible bounding box containing all possible measurements.

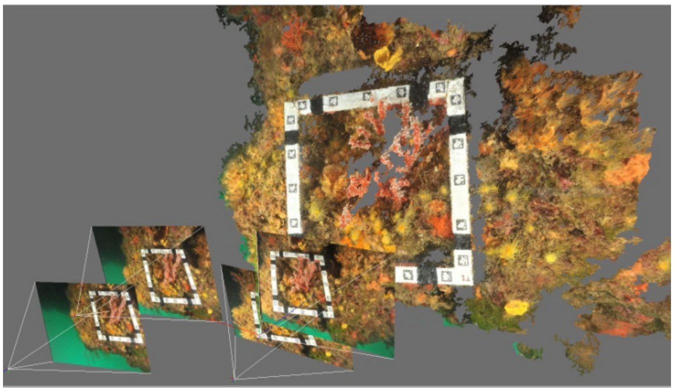

Figure 5. 3D visualization of the four oriented photographs and the scene after densification process.

D. Conclusions and future work

The use of underwater photogrammetry is already used to obtain novel information on the size-structure population dynamics of red coral which provide new quantitative evidence on the effect of harvesting and the recovery of red coral populations dwelling in marine nature reserves. Likewise, for the very first time we obtained reliable measurements of height growth rates for this species. The photographic records were also useful in quantifying the necrosis rates on the populations affected by mass mortality events related with anomalous warming. In this study we focused in only one species, the red coral, but photographs contain information about many other species which could be analyzed in the future to provide better global information on the functioning of benthic communities. The use of underwater photogrammetry was proven very valuable, but a new avenue of applications for the study of such complex communities is already available with the development of affordable geo-referenced mosaic techniques. These mosaics will offer marine biologists new data sets of spatial related information which was simply unachievable only a few years ago.

VI. Conclusions

The work presented here is built on many years of interdisciplinary work between marine biology, underwater archaeology and computer science. In addition, a close collaboration between academic laboratories and high-tech private companies was mandatory in order to achieve the goals.

The project is now mature and close to be fully operational. We are still working on marine integration in a small ROV and also on a real-time process in order to have continuous feedback on-board of the survey performed by the ROV. A draft mosaic and a 3D model can be computed on the fly using synchronized video cameras. We are working on a hybrid system, merging high- and low-resolution cameras in order to be able to process results in real-time as well as to be able to process results off-line with a high quality, as presented in section IV of this paper.

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