High Accuracy Underwater Photogrammetric Surveying

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Abstract – **The evolution of underwater photogrammetry allows to realize 3D models of submerged object and structures throughout the use of rapid and efficient procedures either in terms of data acquisition and data processing. These procedures are based on solutions that are applied using natural control points, signalized markers and tie points; the most common algorithms are based on Structure from Motion (SfM) approach. The limit of these applications is sometimes due to the final accuracy, especially when the goal is a centimeter level of accuracy. This accuracy should be necessary when dealing with a survey devoted to deformation control purposes. An example is the underwater photogrammetry for the determination of coral growth; it is effectively a movement or a deformation detection issue where the geometric change is almost at centimeter or few centimeters accuracy level.**

When dealing with deformation control applications, a geodetic network is essential to realize a stable and unambiguous reference frame through the accurate and permanent installation of Ground Control Points (GCPs). Such a network, indeed, permits a robust reference frame for the georeferencing of images blocks in the different époques of data acquisition. Therefore, the comparison among subsequent photogrammetric restitutions is based on homogeneous 3D models that have been oriented in the same absolute reference system.

The photogrammetric survey is based on a methodological approach especially adapted to underwater biometry (like coral growth determination) and to underwater archaeology. The approach is suitable both for modeling objects of relatively reduced dimensions and for structures with a length of ten meters or more, such as coral barriers, wrecks and long walls.

The paper describes underwater photogrammetric surveys on sites at different extensions, the geodetic GCPs reference network installation and measurements (distance and elevation difference observations) as well as preliminary results of the network adjustment. A brief description of image acquisition at a different scales and the resulting 3D model of first campaign are also shown.

I. INTRODUCTION

High-precision photogrammetric surveys are traditionally performed using stereoscopic data acquisition mode and three-dimensional traditional computation by in situ calibration to calibrate camera and lens [1, 2].

However, the stereoscopic restitution process is rather laborious in water and is particularly suitable when the object to be detected is small in size. Conversely, when facing relatively large objects, where multiple passes are required to capture images and multiple blocks need to be adjusted, then the traditional photogrammetry becomes very burdensome both during the acquisition of images and especially during the three-dimensional processing phase.

Low-cost photogrammetric procedures have been developed, but they are still inefficient especially for the creation of the 3D models and for the analysis of the same model [3, 4]. The recent diffusion of Structure from Motion (SfM) techniques for 3D image reconstruction has allowed its diffusion in various fields: from territorial, to archaeological and underwater [5].

SfM techniques involve typical Computer Vision algorithms that allow semi-automatic photogrammetric resolution of the problem. The execution of the survey is further streamlined and speeded up, feature particularly helpful in a submerged environment, images can be acquired while moving around the object, hence the term "from motion", and no stereoscopic approach is required or the parallelism between the optical axis of the cameras. Coordinate determination of some known points, however, is still required in the SfM to tie and georeference the final 3D model. Some experiments have been carried out in a submerged environment in order to reconstruct plants, platforms, control the seabed and evaluate the health status of coral reefs [6] but the SfM-based methodology in this environment is still almost unexplored.

The aim of the work is to obtain three-dimensional models of good accuracy (centimeter or sub-centimeter levels) of objects of relatively large dimensions (10 and more meters) at subsequent periods in order to monitor and to quantify the phenomenon evolutions by estimating movements and / or deformations of the investigated underwater environment. By georeferencing the 3D models as generated at any survey time with respect to the robust and accurate geodetic network, it is possible to determine the coordinate variations with high precision (centimeter level of accuracy) and consequently to monitor the phenomenon. An important application, for example, is the determination of the growth rate of living elements on coral reefs.

A. *The project and the test site*

Some experiments have been recently carried out in the coral reef in the northern part of Moorea (French Polynesia) [7] within the *Moorea IDEA (Island Digital Ecosystem Avatar)*, a research project for digitization of the ecosystem of the whole island of French Polynesia. Researchers' efforts are leading to the implementation of models for the simulation of complex socio-ecological systems that affect the entire island, meant both a natural and human environment. *Moorea IDEA* is the realization of an *avatar* of the island system, replicable also in other realities, so that Authorities and Administrators have predictive, preventive, participatory and personalized tools in support of sustainable behaviors.

The activity described in this paper and developed by the Geomatics Laboratory of the University of Modena and Reggio Emilia, is part of the mentioned project and aims to develop an efficient and low cost methodology for assessing the growth of coral reefs. The discovery of changes and trends in the development of the reef will then be correlated with changes in the chemical-physical characteristics of the waters and will quantify the effects on one of the environments that make up the complex ecological system of the island. The purpose of the experiments was to outline a methodology useful for controlling the growth of the coral reef (estimated at about 10 mm / year), an application similar to a deformation control. Some critical issues and specific requirements arose in facing the problem with the same approach of traditional case studies. In particular, the need to monitor a phenomenon over time has required the development of suitable markers to materialize the reference system in a stable and unambiguous way over time, thus ensuring model comparability and monitoring of time-increasing phenomena. Such markers are also needed in the process of creating a reliable and usable model; in fact, these markers provide both GCPs for georeferencing the final model and the constraints for SfM processing, allowing to reduce the distortions generated during the concatenation of the images. This allows to calibrate the cameras: in underwater conditions, it is impossible to use metric or pre-calibrated cameras because of the high costs and the high variability of operating conditions. Depth, temperature, salinity, illumination, refraction of optical beams vary continuously, it is therefore necessary to recalculate camera calibration parameters at each location in different times. The calibration procedure consists of a in situ self-calibration, that is a calibration to be carried out at the time of image acquisition as it is dependent on the physical conditions of the environment. Calibration is performed through captured images and constraints in order to calculate and optimize the internal orientation and lens distortion parameters for that particular survey [8].

II. UNDERWATER SURVEY: EQUIPMENT, DATA ACQUISITION AND REMARKS

Special equipment with ad-hoc measuring devices have been developed for the specific application and experienced during tests. Authors focused on a system for identifying GCPs within the image capturing step. Moreiover, attention has been paid to devices suitable to realize a stable and unambiguous reference frames based on observable markers. In particular, the experiments aimed to define a methodology for determining the most accurate coordinates of GCPs within the local reference system. As a result of first measurement campaigns, specific markers and devices for the optimization of underwater GCP measurements have been designed. In detail, Authors produced:

- for distance measurements, a graduated telescopic bar and for distances greater than 5 m a metal metric cord. These devices allow more robust distance measurements by minimizing the flexure of the measurement device due to marine currents (Fig. 1, top);
- for leveling observations, a laser pointer system for collimating the staff (Fig. 1, second line left) and a system for blocking the staff and facilitating the verticality during the measurement (Fig. 1, second line right);
- for angular measurements, a special goniometer equipped with a laser pointer for the approximate measure of horizontal angles (Fig. 1, third line);

Fig. 1. Special low-cost equipment as developed for underwater surveying; from top to botton: graduated bar for distance measurements, laser pointer on a tripod (left) and staff mounting adaptor (right) for leveling measurements, goniometer with laser pointer for raw azimuth measurements, markers (left) with exchangeable adaptors, one for distance measurements (middle) and the other to be identified as GCP in SfM process (right).

- exchangeable special adaptors that allows alternatively the distance measurement, the installation of the leveling staff, the installation of the goniometer for angular measurements and the location of the photogrammetric marker (Fig. 1, bottom). The markers are connected to the ground by means of a threaded bar that is screwed to the ground and allows the installation of the measuring device. This bar is needed to 'lift' the marker and overcome the obstacle of the coralline concretes, making it observable and measurable from the other points of the network or station points. Two types of bars have been used at the different lengths of 20cm and 40cm.

Concerning the geodetic network, measurements of each distances between the GCPs have been repeated in order to check the absence of major errors, to construct a small statistic on the data and mainly to adopt the highest possible redundancy.

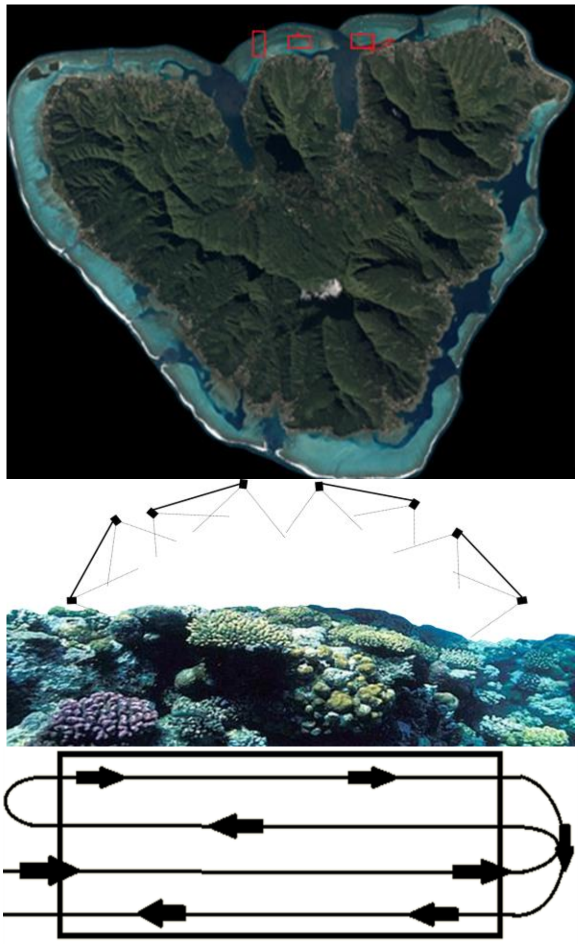

Fig. 2. Moorea (French Plynesia) with location of test sites (top picture); sketch of the images capture. The diver follows the path as shown in the bottom piture and the camera attitude follows several fly altitude (2.5 and 5 meters) and multiple orientations (middle picture).

It has been verified that the 40 cm connection bar, used to lift the marker and carry out the measurements, is affected by unacceptable deviations from verticality, so only the use of 20 cm bars was taken into consideration in order to reduce non-vertical effects. Unfortunately, the goniometer does not allow high precision measures because of the difficulty of reading values in the underwater environment. Consequently, the accuracy of the measured horizontal angles is absolutely not comparable with the accuracy of the distance and the difference in elevations, so these values have not been used in network adjustment.

Concerning the image acquisition, a high performance camera (the Lumix with 19 mm focal length) and a cheaper cameras (a set of 5 GoPro with wide-angle focal frames) have been used [7] (see Fig. 2). The images have been captured with the same lens at a distance (dive altitude) of about 2.5 m and about 5 m in order to verify the potential for use at different scales (see Fig. 2).

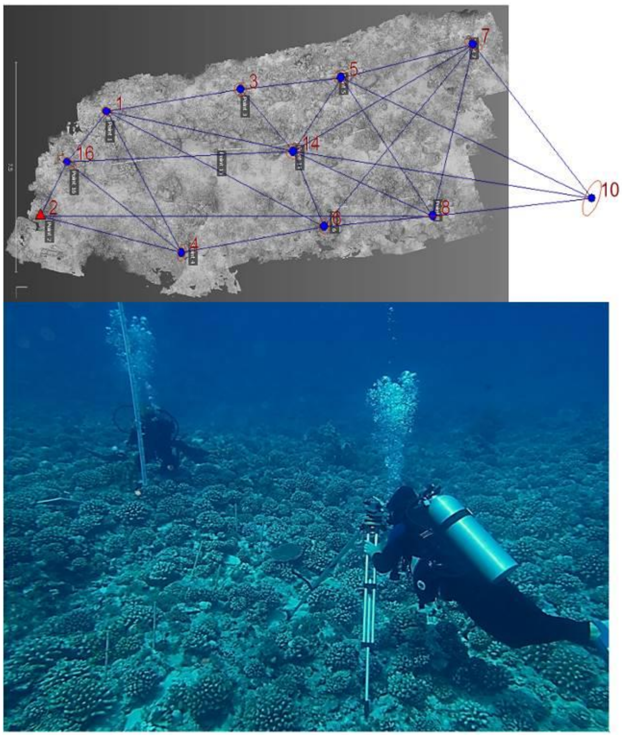

Fig. 3. Fringing reef test site: picture at top shows the geometry of the geodetic network that realizes the reference frame for processing and comparing 3D models. In the bottom, a picture during leveling measurements with a diver pointing the staff with the underwater laser pointer and the other posing the staff vertically over the marker.

The area under investigation is surveyed by flying over several times, varying the camera orientation to ensure a high overlap of the images and the completeness of the reconstruction. The GCPs, securely installed within the reef, will serve as a constraint during model building, image concatenation, and to provide a stable and common reference system for surveys that are carried out in different periods.

III. PRELIMINARY RESULTS

A. *Fringing reef transect*

The Fringing reef test site is characterized by a network that extends for a length of about 15 meters and a width of about 5 meters consisting of 11 benchmarks (identified by markers) at varying distances between 3 and 9 meters (Fig. 3, top). Elevation measures (Fig. 3, bottom), distance and azimuth angles have been carried out.
The preliminary accuracy results of network adjustment are shown in table 1. The average value is +/- 2 cm for both planimetry and elevation. The accuracy of measurements were respectively +/- 1.5 cm for the distances and +/- 2.5 cm for the height differences. Even if it is a preliminary result, the accuracy that we obtained in coordinates determination are really close to those waited for and it is a starting point to understand the period which a certain amount of coral growth should be detected on the basis of estimated growth and measurements accuracy.

Table 1. Fringing reef geodetic network –Preliminary accuracy results of the 3D adjustment process.

ID	σE [m]	σN [m]	σH [m]
1	0.016	0.024	0.025
2	0.000	0.000	0.000
3	0.017	0.036	0.021
4	0.013	0.023	0.018
5	0.017	0.019	0.024
6	0.016	0.025	0.022
7	0.022	0.019	0.024
8	0.020	0.000	0.023
10	0.020	0.039	0.026
14	0.013	0.026	0.019
16	0.020	0.025	0.018

Fig. 4. Fringing reef test site: preliminary 3D model of coral reef as obtained on the bases of August 2016 survey campaign.

B. *Fore reef spot sites*

Five smaller extension areas, about 5 meters square, have been built by means of four markers at the vertices of a square and one fifth at the intersection of the two diagonals. The areas are located outside the reef and are subject to study as they are characterized by very recent and relatively strong creels. Here again, the distance and level measurements of all GCPs have been carried out.
Figure 5 shows a picture and a sketch of sample areas that have been investigated (numbered as 16, 17, 18, 19 and 20, respectively).

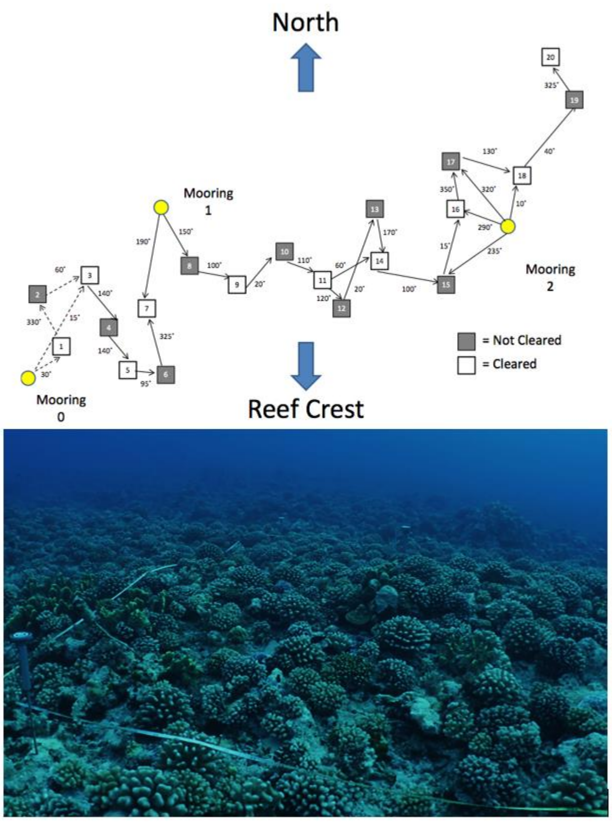

Fig. 5. Fore reef site: the plot at top shows the geometry of the geodetic network that realizes the reference frame for processing and comparing 3D models (all five sites are shown). In the bottom, a picture showing the site, about 5 meters square, ready for capturing images (markers with photogrammetric adaptor are installed).

It has been decided to work even on few areas of reduced size because it should be easier to join high accuracy in GCP determination, so in 3D model comparison in time with respect to longer transect. In the meantime a very large area of coral reef should be investigated using spot sampling results of several small sites measurements.
The data processing of 5 spot sites is under working. Indeed, the poor redundancy coupled with some observations affected by errors, thus excluded from the computation, provide preliminary results that are not consistent, with the accuracy good enough for some sites and worse for the others.

IV. CONCLUSIONS

Image acquisition and data processing procedures have been optimized for a photogrammetric survey in an underwater environment with the purpose to get a high accuracy (centimeter level) 3D model. Instrumentation and methodologies have been especially designed, developed and tested to ensure a significantly high accuracy for applications in the underwater context.
The potential for utilization relates to the survey of objects or structures of great extension (wrecks, walls, reefs) or characterized by slow motion where the goal is the deformation control (biometrics, coral growth). Specifically, in the context of coral measures, it is possible to estimate the rate of growth; such a velocity may be related to the variation of weather parameters in the investigated areas. The research project is precisely focusing on the risks induced by climate change for coral reef conservation by testing the methodologies in Moorea, French Polynesia.
The major effort until now is the creation of a reliable geodetic reference network acting as stable reference frame for the comparison of 3D models. This is practically application of surveying for deformation control. Results achieved in the geodetic network adjustment of the large test site, Fringing Reef, show an average accuracy of 2 cm (both horizontal and vertical) for the adjusted coordinates on the basis of redundant distance and elevation difference observations. Therefore at the moment, if the coral growth is assumed to be 10 mm per year, such results encourage to repeat the developed methodology every 2-3 years in order to be sure to highlight whether a real and significant growth occurred or not in the reef. Concerning the smaller test sites, the Fore Reef ones, results suggest a deeper analysis of the raw measurements and probably the integration with additional measurements. Anyway, the interest for the achievable accuracy in small networks is of great importance because they could act as sample areas to be investigated through the photogrammetric survey in order to monitor the coral growth.
The realization of the surveying and monitoring system for coral reef applications as well as the determination of small growth rates are both of scientific and economic concerns. The accurate quantification of coral growth velocities allow to plan conservation interventions and mitigation actions; this approach also has a positive impact on the local economy: remember that for many tropical islands the tourism related to the exploration of coral reefs is one of the most important sources of livelihood for the local population.

REFERENCES

1. J.G.Fryer, C.S.Fraser, “On the calibration of underwater cameras”, Photogrammetric Record, vol.12, No.67, April 1986, pp.73-85.
2. M.Shortis, “Calibration techniques for accurate measurements by underwater camera systems”, Sensors, vol.15, 2015, pp.30810-30827, doi:10.3390/s151229831.
3. A.Capra, “Non-conventional system in underwater photogrammetry”, ISPRS Archives, vol.XXIX, 1992.
4. A.Capra, “Application of underwater photogrammetry for the deformation control of submerged objects”, ISPRS Archives, vol.XXX, 1994, pp.16-22.
5. M.J.Westoby, J.Brasington, N.F.Glasser, M.J.Hambrey, J.M.Reynolds, “Structure-from-Motion photogrammetry: A low-cost, effective tool for geoscience applications”, Geomorphology, vol.179, 2012, pp.300-314.
6. A.Lavy, G.Eyal, B.Neal, R.Keren, Y.Loya, M.Ilan, “A quick, easy and non- intrusive method for underwater volume and surface area evaluation of benthic organisms by 3D computer modelling”, Methods in Ecology and Evolution, vol.6, No.5, 2015, pp.521-531.
7. T.Guo, A.Capra, M.Troyer, A.Gruen, A.J.Brooks, J.L.Hench, R.L.Schmitt, S.J.Holbrook, M.Dubbini, “Accuracy assessment of underwater photogrammetric three dimensional modelling for coral reefs”, ISPRS Archives, vol.XLI-B5, 2016, pp.821-828, doi:10.5194/isprs-archives-XLI-B5-821-2016.
8. A.Capra, M.Dubbini, E.Bertacchini, C.Castagnetti, F.Mancini, “3D reconstruction of an underwater archaelogical site: comparison between low cost cameras”, ISPRA Archives, vol.XL-5/W5, 2015, doi:10.5194/isprsarchives-XL-5-W5-67-2015.