

Evaluation and comparison of non-contact measurement techniques for the observation and shape reconstruction of sessile benthic organisms

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Abstract – The idea underlying this proposal is to understand the exploitability of scanning technologies for studying and observing the shape variability of marine sessile benthic organisms with particular focus on corals. This is a preliminary study in order to compare the different systems, laser-based and photogrammetric techniques, for 3D shape reconstruction and color information. The approach to the study has been schematized by using several solutions, with the aim to investigate performance in terms of operation, process reliability, quality and metric accuracy of 3D models obtained by processing with image-based techniques. The investigation involves the use of a pool to build laboratory tests characterized by different complexity of structures (especially in terms of size and shape) in an underwater environment. Results show the difference between 3D models obtained by a 3D color laser scanner prototype (RGB-ITR) developed in ENEA ArtVisLab (Frascati) and standard commercial cameras. The difference in terms of color is highlighted.

I. INTRODUCTION

Habitats are multilayered entities, with diverse and abundant sessile organisms such as macrophytes and invertebrates. Usually, these organisms have a complex morphology and 3D structure and they represent habitat formers for other associated plant and animals (engineering species) [1]. In hard bottoms, such organisms are represented mainly by sessile colonial invertebrates, such as sponges, anthozoans (corals and gorgonaceans) and bryozoans. One of the main ecological role of these habitat formers is to modify the bottom topography and to increase the architectural complexity and the biodiversity at different scales. In addition, many of such engineering, or bioconstructor species, especially among scleractinian corals and sponges, are quite plastic in their morphology and have the capacity to change their shape according to local environmental conditions [2]. While in some case

they also represent species sensitive to climate changes and therefore bioindicator of water warming, and can register past climatic events in their skeletons [3, 4]. For these reasons, there is the need to study populations and assemblages of sessile habitat-former organisms (mainly anthozoans) to describe the modification they made to the bottom topography and their ecological implications, with the use of underwater 3D sensors developed to operate in air conditions. This paper is part of a larger project and its aim is to provide raw 3D data that have to be post-processed to obtain metric 3D information. In addition to the metric accuracy of the examined objects, in this context the colorimetric information are a very important aspect still not widespread in underwater applications. The best colorimetric measurement system to capture the spectroscopic properties of each submerged object is investigated.



Fig. 1: An example of coral reef with sessile organisms

II. STATE OF THE ART

3D shape reconstruction of underwater targets has to meet some basic requirements [4]:

- Capability of working in cloudy waters, in non-uniform lighting conditions and with external objects that could interfere with the scene framed

(e.g. external objects projecting shadows or obscuring the target);

- Capability of investigating relatively large areas
- Fast and easy-to-do processing of data acquired *in situ*.

In the state of the art, several methods for recovering 3D information of an underwater scene are described. They can be generally classified, according to the technology and measuring principle used, into active and passive techniques [5]. Active optical methods use radiations (normally light) that act as a probe for the surface. However, it should be taken into consideration that not all these methods provide colorimetric evaluation, structural morphology and distribution, at the same time.

Sonar-based detection of underwater objects is an example of an active one. This method is widely used in underwater measurements but it is best suited for long distances of measurement (which implies less spatial resolution). It usually relies on multi-beam sonar systems [6]. The set of echo signals corresponding to a number of very narrow beams is received and recorded during a single ping. The beams have different transmission angles and each beam gives the possibility to calculate the 3D coordinates of the seabed surface. However, this method can not provide color information.

Underwater laser scanner system is another active method, which uses a trigonometric approach [7]: the sensor sends a laser line to the object surface, and an optical sensor receives the return signal. It is based on scattering principles similar to active sonar, but it provides better measurement accuracy. Indeed, measurements from dense laser point clouds will in general be much more accurate than those taken from relatively sparse sonar point clouds. Additionally, laser systems are not affected by confined spaces prone to acoustic echoes. The sensor head can be mechanically rotated in order to capture a series of adjacent profiles of the object and obtain a 3D point cloud of the target surface. Although they need to be combined with a camera to integrate the distance measurement of the target points with the color information [8]. The propagation model of light radiation in water is the main issue in using laser scanner techniques on underwater applications. Light is not transmitted through water as well as in air, and the effective range of laser systems is significantly higher in most of terrestrial applications rather than in underwater environment.

For what concerns passive optical methods, they are able to reconstruct the 3D shape from photographic images, without interacting with the object [9]. In this case, artificial light is only used to illuminate the scene. Most of photogrammetric techniques use the *Structure from Motion (SfM)* algorithm, which reconstructs the 3D structure of the scene from a sequence of monocular views. This method represents a cheap solution for 3D shape measurements in underwater applications. However, such approach presents some limits related to cloudy waters,

untextured grounds and excessively dark environments.

This study presents an assessment of photogrammetric techniques in comparison to a novel laser-based approach for coral surface reconstruction. In the frame of this work, the color 3D models are acquired by RGB-ITR Laser Scanner prototype to evaluate the terrestrial scanner features for detecting subsea objects. This underwater laser systems integrate the distance measurement of the target points with the color information of the object using amplitude modulation of three monochromatic laser sources (red, green and blue wavelength) [10]. The result of the combination of these two data is a very high-precise distance and color measurement. This results are compared with photogrammetric 3D data and evaluated from a qualitative and metric perspective also in relation to the characteristics and peculiarities of the detected objects.

III. MATERIALS AND METHODS

Three samples with different shape complexity were tested for this study: a marine sponge, named *Ircinia Campana*, was the low complexity target; while a natural white coral rock branch, named *Pocillopora*, and a red coral, named *Corallium Rubrum*, were respectively used for the medium and high complexity. Moreover, in the experimental laboratory two different technologies were used for data capture and image-based techniques for data processing.

A. RGB-ITR Laser Scanner

RGB-ITR (Red Green Blue–Imaging Topological Radar) system is the 3D color laser scanner prototype realized by ENEA laboratories. The system is characterized by three monochromatic laser sources at 650 nm (red), 532 nm (green), 450 nm (blue) wavelengths. Amplitude of each wavelength are modulated with a high and a low frequency, first one to obtain a higher precision measurement in a smaller range and the second one to measure the distance in a bigger range, between the center of the optical head and the target [10]. The simultaneous collection of distance and color information are extracted respectively through phase-shift and amplitude of back-reflected waves by the target surface. In detail, the distance information is derived from equation (1):

$$D = \frac{v\Delta\phi}{4\pi f_m} \quad (1)$$

Where f_m is the modulation frequency, $\Delta\phi$ the phase difference between the reference modulating wave and the signal back-reflected by the target, and v the light speed in the medium [11].

Calibration system is obtained by moving a certified white target (Spectralon STR-99-020, diffuse reflectance 99%), at several distances and striking it with the three laser sources. The normalized image is given by the ratio between the amplitude value of the three wavelengths reflected by the target surface and the calibration target (Fig. 2).

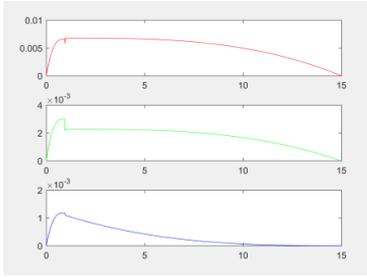


Fig. 2: Calibration curves of each channel, obtained illuminating the white target with the three laser beams of RGB-ITR system.

This system is used to benefit from the prototype to expand the terrestrial scanner features for detecting objects in the water. In this context, the refractive index of the water is considered in distance equation (2):

$$D = \frac{v\Delta\phi}{4\pi n f_m} \quad (2)$$

Where: $n = 1.33$.

An accurate digitization of two submerged sample, the *Corallium Rubrum* and the *Pocillopora*, was performed in May 2016 by means of the RGB-ITR laser scanner. The first one was immersed in an aquarium filled with relatively clean water and a black background to avoid laser dispersion was used. In this case, light waves had to pass three different kind of medium (air-glass-water). The second one was immersed in a matt bucket to avoid dispersion due to glass, with the laser pointed perpendicularly in the bucket. In this way, the laser devolved directly into the water and there was no the air-glass interface. They were both placed about 1.70 meters from the centre of the optical head. With software packages developed in ENEA [11], it was possible to start scanning by setting the scene capture parameters with Scan System interface (Fig. 3, a):

The three lasers were modulated with a high frequency of 190MHz and a low frequency of 10MHz. The acquired data was processed with Itr Analyzer interface (Fig. 3, b), which enabled 3D point cloud reconstruction. The procedure of image processing is:

- “Open ITR project” to select and load the project file;
- “Image normalizer” to change the range of pixel intensity values by means of the calibration using the white target (Fig. 4);
- “Complete mesh” to visualize the 3D object;
- “Create mask” to select thresholds from histogram of the 3D object;
- “Export mesh” to save the mesh in PLY format with texture;
- “Register mesh” to register two mesh with different angles of the same scene.

With the open source system, called MeshLab, the object’s surface was edited, cleaned and filtered.



Fig. 3: (a) Scan System interface; (b) Itr Analyzer interface.

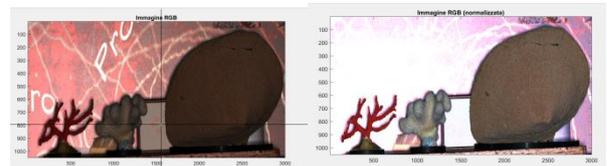


Fig. 4: An example of normalized image of the scene at 5m in air, by RGB-ITR system.

B. Photogrammetry

In the other way, photogrammetry provides metric information, such as shape, size and location of real objects by measuring and interpreting photographic images. When objects are acquired at a distance less than 300 m from the camera, it is possible to define photogrammetry as “close-range”. In this study, a *multi-image approach* has been used. The process was divided into two main phases:

- 1) Calibration, necessary to correct both mechanical and optical systematic errors of the photographic device.
- 2) Acquisition and processing phase, in which the multiple images from different positions was captured and the transformation from 2D image coordinates to the corresponding 3D world coordinates was started, characterizing the shape and size of the detected object.

Camera calibration in the context of three-dimensional machine vision is the process of estimating the internal camera geometric and optical characteristic (intrinsic parameters) and the 3-D position and orientation of the camera frame relative to a certain world coordinate system (extrinsic parameters) [12]. To calibrate the camera, it was necessary to take multiple images of a calibration pattern from different angles: a typical calibration pattern is a checkerboard. The checkerboard was affixed to a flat surface, at approximately the same distance from the camera as the objects to be measured and the size of a square was 15 mm (Fig. 5). It were used about 20 images of the pattern from several positions to obtain position and orientation coordinates (Fig. 6), focal length information, main point position (x_0, y_0), and some additional

parameters used to model errors due to, for example, lens distortion [13].

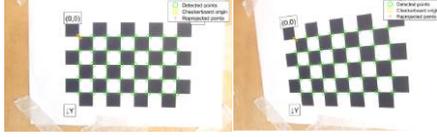


Fig. 5: Detected points, checkerboard origin and reprojected points

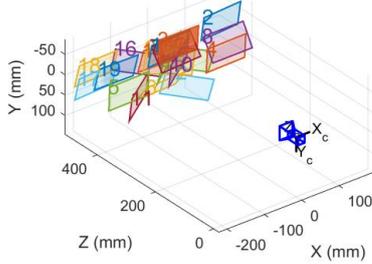


Fig. 6: Extrinsic parameters visualization

After calibration, accurate 2D photos around the submerged objects from multiple view were needed in order to estimate imaging distances and color informations. The experimental setup included the following waterproof cameras: COOLPIX AW100 and GoPro Hero 3. Data was collected with this two different digital cameras and several grip modes (number of images, grip distances, different resolutions) to compare the performance of cheap underwater cameras for metric applications. The images obtained by the first camera has pixel dimensions of 1024 x 768, a resolution of 300 dpi, focal length of 5 mm and a color depth of 24 bits. Second camera has pixel dimensions of 4064x2704, a resolution of 72 dpi, focal length of 2.77 mm and a color depth of 24 bits. Main difference between two cameras is in the 170° wide-angle lens of GoPro, corresponding to a wider viewing angle.

Cameras were positioned in a test pool at about 10 cm from the target and the scene was illuminated by ambient light. 3D dense point cloud, mesh and texture were generated by means of the commercial software ©Agisoft PhotoScan Professional product using *Structure from Motion (SfM)* approach [14]. The SfM algorithm provides the structure of the scene, through the position of the numerous matched features, in addition to camera positions and internal calibration parameters.

The procedure of image processing and 3D model construction is:

- “Camera calibration” to insert manually the camera parameters;
- “Align photos” to identify and match a sparse set of points between the images;
- “Build dense cloud” to match and build a dense set of points;

- “Build mesh” to obtain polygonal surface from point cloud;
- “Build texture” to apply textures on the mesh.

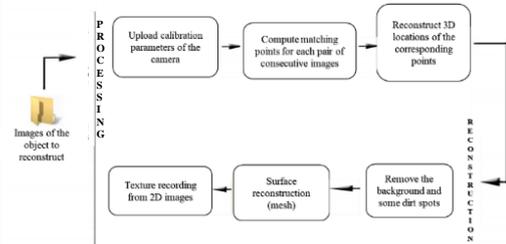


Fig. 7: Photogrammetric 3D reconstruction procedure schematized

IV. RESULTS

The image processing provided the accurate 3D object reconstruction.

Corals reconstructed by RGB-ITR system are characterized by high resolution and high contrast. During the acquisition phase, some external factors difficult to control such as interference due to aquarium glass or to the presence of water, may alter the 3D relief information. It is possible to see the *Corallium Rubrum* model (Fig. 8b) affected by the refraction due to both glass and water, and the *Pocillopora* (Fig. 8d) affected only by water refraction. The distance measured is more accurate in the second case than the first one. In general, the 3D models are geometrically loyal to the reconstructed object. For what concern the color information, it was not possible to insert the white target into water, so the color range of the models is not correctly calibrated. Table 1 shows the acquisition times, number of vertices and faces characterizing the surface and the distances between optical head and targets.

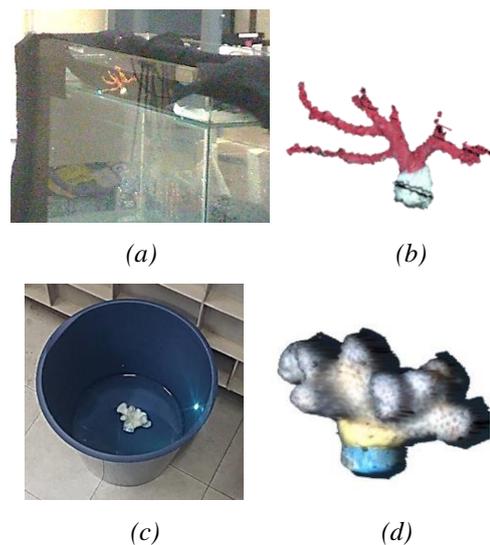


Fig. 8: *Corallium Rubrum* in aquarium (a) and 3D model (b); *Pocillopora* in a bucket (c) and 3D model (d)

For what concern photogrammetric results, there are substantial differences in reconstruction, depending on the different kind of camera used. Fig. 9 shows the *Ircinia Campana* model obtained by COOLPIX AW100 (a) and GoPro (b) cameras.



Fig. 9: Differences between *Ircinia Campana* scanned by COOLPIX (a) and GoPro cameras (b)

In particular, it is possible to see the lower resolution of the model obtained by the GoPro. In fact, the mesh is poorly defined, without qualitatively satisfactory results. On the contrary, the COOLPIX provides an accurate 3D shape reconstruction. Furthermore, color properties present some limits related to different environmental lighting. In detail, this effect is highlighted on *Ircinia Campana* scanned by COOLPIX, which presents different color shades. For each structure with different complexity, number of photos acquired by cameras, shooting distance and number of vertices and faces characterizing the surface are described in Table 2 and Table 3.

Table 1. RGB-ITR summary results

Target	Time (min)	Distance (cm)	N ⁰ vertices	N ⁰ faces
<i>Pocillopora</i>	85	170	313171	476705
<i>Corallium Rubrum</i>	50	170	450861	577058

Table 2. COOLPIX summary results

Target	N ⁰ photos	Distance (cm)	N ⁰ vertices	N ⁰ faces
<i>Ircinia Campana</i>	40	18	90366	84659
<i>Pocillopora</i>	46	8	90822	23549
<i>Corallium Rubrum</i>	25	10	16566	31736

Table 3. GoPro summary results

Target	N ⁰ photos	Distance (cm)	N ⁰ vertices	N ⁰ faces
<i>Ircinia Campana</i>	37	21	70753	128057
<i>Pocillopora</i>	44	10	23447	45913
<i>Corallium Rubrum</i>	42	15	18015	34617

The differences between the two scanning systems are shown in Fig. 10.

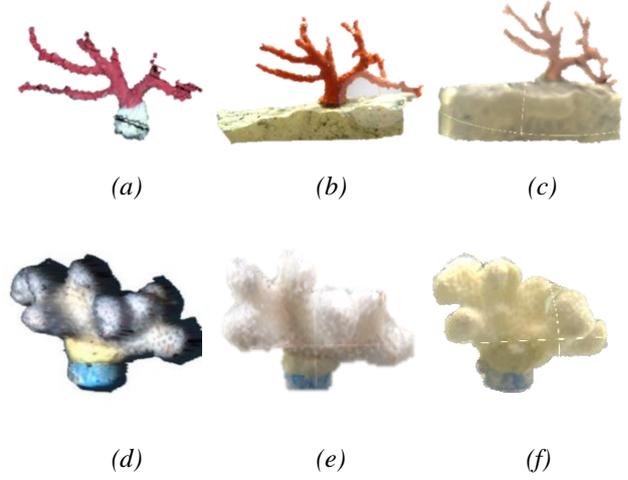


Fig. 10. Comparison between *Corallium Rubrum* and *Pocillopora* scanned by RGB-ITR (a,d), COOLPIX AW100 (b,e) and GoPro Hero 3 (c, f)

It is clear that the RGB-ITR color information is not affected by external light noise while 3D relief is influenced by other external factors, such as interference due to aquarium glass and waterborne. In comparison, it is possible to see that the same corals reconstructed by photogrammetric technique are influenced by external illumination and has a lower resolution.

Number of vertices and faces characterizing the surface obtained by means of the different techniques are shown in Table 4. In the case of laser scan, these values are higher than those achieved by means of photogrammetric scan. However, this does not prove that a greater number of vertices and faces are indicative of better scanning. In fact, more frames of the scene could increase the number of vertices and faces of the 3D model.

Table 4. Comparison between number of vertices and faces of the *Corallium Rubrum* obtained by different scanning techniques

Scanning techniques	N ⁰ vertices	N ⁰ faces
RGB-ITR laser scanner	450861	577058
Photogrammetry (COOLPIX AW100)	16566	31736
Photogrammetry (GoPro Hero 3)	18015	34617

V. DISCUSSION AND CONCLUSIONS

According to results, RGB-ITR system for structural and colorimetric reconstruction has a better performance than

photogrammetry in underwater environment. The 3D laser point cloud is more accurate than photogrammetric point cloud. However, light is not transmitted in water as well as in air and the performances of this laser system is worse in underwater environment than in terrestrial applications. In addition, the long acquisition time of the system is a drawback for the scuba divers. Moreover, a color calibration system is necessary to study for underwater applications.

In the same way, the principle of underwater photogrammetry does not substantially differ from that of terrestrial or aerial photogrammetry. However, also in this case, it is necessary to take into account certain elements that may cause disturbance, as the refraction of the diopter water-glass [15]. The measurement accuracy in underwater 3D reconstruction is considerable lower than in air measurements mainly for one reason. The reason of such lower performances has to be found in target illumination issues: it is necessary to illuminate the measurement object using more light than what could be done in the air. However, the real advantage of using photogrammetry in underwater surveys in comparison with the use of other techniques consists in its simplicity of implementation, its lower acquisition times than RGB-ITR, the diversity of potential results and the relatively cheap cost.

The research of the best underwater scanning technique to perform accurate measurements of volume, surface area and other morphometric measurements of three-dimensional biological objects, without removing them from the sea, represents a valuable contribution to the conservation of current marine flora and fauna. Photogrammetry is more appropriate for rapid low-cost surveys, while RGB-ITR is more suitable for intensive detailed analyse of surface that requires three-dimensional model of community structure, which is analyzed in the laboratory and archived for future reference.

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