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Abstract

Over the past decade, photogrammetry has grown considerably thanks to technical advances in digital cameras and computing performance. Popular in terrestrial applications with the development of UAV acquisition, photogrammetry provides access to accurate scene reconstruction, high-resolution measurements, and temporal comparisons with a wide range of geolocated and scaled 2D and 3D supports. Nowadays, photogrammetry represents a particular challenge in the underwater field such as environmental monitoring, marine construction, technical inspection, and archaeology. Our study aims to develop underwater acquisition protocols and new tools for marine resources surveys and management to understand the role of 3D characteristics in both coral reefs and artificial structures. Two specific protocols were designed and optimized to reconstruct from coral colonies to coral reefs and artificial structures (up to 500m²) with a mean resolution of 0.05cm/pixel. Here several quantitative descriptors based on 2D and 3D metrics (such as slope, length, surface, volume, rugosity) were calculated for morphological studies and temporal comparisons. The photogrammetric technique now offers higher quality and accuracy tools compared to traditional survey methods. These advantages make possible to access to new scientific surveys of underwater ecosystems and as environmental management tools may prove to be valuable for future.

Introduction

Coral reefs, covering only 0.1% of the oceans, perform essential ecological functions by hosting more than 25% of the world's marine biodiversity. These ecosystems are threatened by anthropogenic activities, climate changes and catastrophic natural events with 54% of them being critically endangered (Bozec et al., 2015; Hughes et al., 2017; Cornwall, 2019). With the rising of oceans temperature, acidification and oxygen depletion, coral reefs are facing unprecedented challenges. Being the most ecologically and structurally diverse ecosystems of the planet (Yanovski & Abelson, 2019), one important feature that is being studied is structural complexity (Chabanet et al., 1997; Beck, 2000; Commito & Rusignuolo, 2000; Graham & Nash, 2013; Mohd-Azlan et al., 2015). In the past years, studying marine architecture of habitats was difficult using in situ methods, due to technical limitations in measuring three dimensional structures while underwater, but evenso became a focus of surveys during the two last decades (Bythell et al., 2001; Knudby & LeDrew, 2007; González-Rivero et al., 2014).

With the emergence of new technologies such as photogrammetry (Cocito et al., 2003, Bruno et al., 2011, Westoby et al., 2012), LIDAR, multi/hyper spectral, and ecoacoustics (Elise et al., 2019), new underwater survey methods can be developed to better understand three dimensional structures and their links with ecosystems and provide improved tools to monitor and manage marine resources.

Photogrammetry allows high fidelity 3D reconstructions using images taken from different angles around a subject (Westoby et al., 2012; Raoult et al., 2017). These reconstructions provide an accurate quantification of various embedded metrics (Figueira et al., 2015; Burns et al., 2016) in a non-invasive way which is particularly valuable for temporal comparisons (Fukunaga et al., 2019). Despite the limitations of underwater photographic data acquisition including light refraction, varying water transparency, focal length changes, and the lack of geographical positioning information needed for a precise alignment of images, photogrammetry showed up an important advantage over traditional methods when assessing the 2D and 3D characteristics (Marre et al., 2019) of coral colonies and reefscape configurations (Burns et al., 2015a/2015b/2019; Zawada et al., 2019).

Our aim was to develop specific protocols to ensure accurate sub centimetric reconstructions and precisely quantify their physical characteristics without observer bias. We also aimed to generate highly accurate, user fiendly, easy to implement and low-cost tools to describe the complexity of habitats using a multi-scale cartographic approach (from colony to reefscape) and a structural approach (complexity, roughness, typology). Here we present underwater photogrammetry as an interative tool with accurate and quantitative indicators for the assessment and monitoring of coral reefs, that can be extended to nearshore artificial structures. This applies to the entire ARC approach (Avoid, Reduce, Compensate) ranging from feasibility studies (site selection), to impact mitigation (eco-design, choice of materials), and the implementation of compensatory measures for marine biodiversity and ecosystem services.

1. Materials and methods

1.1 Datasets and study sites

In order to use contrasted morphologic datasets, from 2017 to 2019 we acquired 131 isolated coral colonies, 29 reef seascapes, and seven artificial structures (artificial reefs, rockfill, accropodes©) covering up to 500m² located in various areas: Reunion Island in the Southwest Indian Ocean, Europa Island in the Mozambique Channel (part of the French Scattered Islands), and New Caledonia in the Southwest Pacific Ocean. (Figure 1 and Table 1).

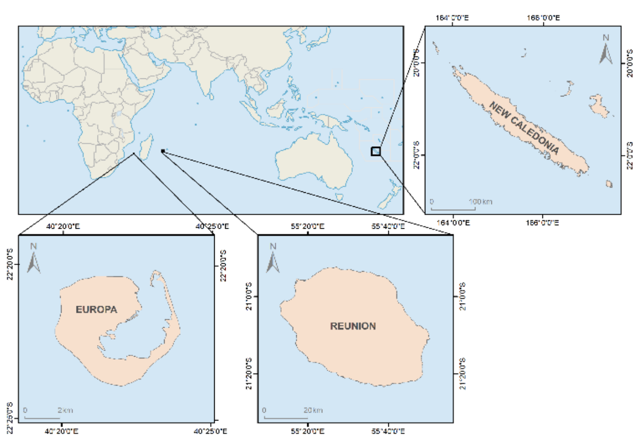


Figure 1. Location maps of the study sites

Location	Coral colonies	Reefscapes	Artificial structures
Reunion Island	95	5*500m² 7*250m²	7
Europa Island	15	9*250m²	
New Caledonia	21	8*250m²	

Table 1. Datasets per location

1.2 Photographic equipment

The camera equipment consisted of a Sony Alpha 7 Mark 2 (24 Mega pixels sensor) equipped with a Sony Zeiss Vario-Tessar FE 16-35mm F4 lens (SEL1635Z) placed in a Nauticam NAA7II underwater housing with a Nauticam 180mm dome port and without artificial lights. The camera was set to manual mode in ISO auto with a limitation of 100-3200, with a minimum shutter speed of 1/250sec to avoid motion blur. The photographer adjusted the aperture to keep the entire subject in focus. Focus was set to AF-S auto in wide mode to have multiple focus points over a given scene. All shots were taken in RAW format on a 128Gb SanDisk Class 10 U3 Extreme Pro SD card.

This configuration allowed us to maximize the coverage of the studied subject with a wide-angle lens while keeping a fine precision (real size of a pixel) thanks to the photographic sensor resolution and without too much distortion (-3% approximatively) and curvature on the edges of each shot (Figure 2). A wide-angle lens or fisheye lens with greater lenticular distortion usually leads to projection concerns or curved reconstruction when computed.

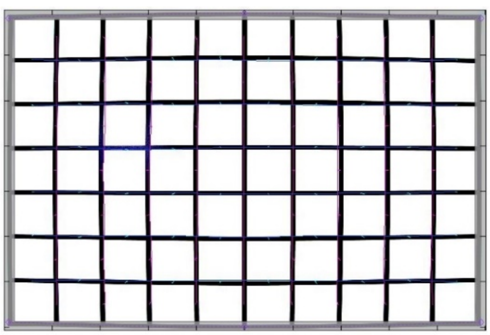


Figure 2. Sony FE 16-35mm F4 lens distortion (set at 16mm)
© Klaus Schroiff, 2015

1.3 Underwater calibration

The results of photographic acquisitions can vary due to several parameters. Indeed, the port of the housing (plan or dome), the air/water interface, and light refraction can influence the way that the sensor captures each shot. So, calibration tests were carried out to quantify changes first by photographing objects on a checkerboard and comparing distance, area, and volume measurements of the 2D and 3D reconstruction versus reality, and then by testing various reconstructions to enhance the calibration parameters. Those parameters, and in particular the focal length changes (which changed underwater at 17.5mm) and distortions values, were integrated in our photographic acquisition protocol and reconstruction workflow.

1.4 Photographic acquisition protocols

The key to the success of photogrammetric reconstruction resides in the overlap and angles of view between images. Common softwares such as Agisoft Metashape and Pix4D Mapper Pro recommend a minimum longitudinal (frontal) overlap between images of 75-80% and 60% lateral (side) overlap in most cases. Distance from the subject affects the real size of pixels or GSD (Ground Sampling Distance) and the coverage of each shot as follows:

$$GSD = (SW*D*100)/(F*PW)$$

where GSD = ground sampling distance (cm/pixel)
SW = sensor width (mm)
D = distance from the subject (m)
F = underwater focal length (mm)
PW = number of image pixel - width

$$WC = GSD*PW/100$$

where WC = picture coverage on the seafloor - width (m)
GSD = ground sampling distance (cm/pixel)
PW = number of image pixel - width

That leads to a shorter distance implies a greater number of images but a better precision, as opposed to a longer distance requires fewer images but less precision.

Two photographic acquisition protocols were designed, then optimized from the results of 2D and 3D reconstruction tests. Protocol 1 was developed to acquire small and middle-sized objects, namely isolated coral colonies of varying 3D morphologies, at approximately 30cm distance around the subject with only spherical oblique shots. Protocol 2 was developed for seascapes of up to 500m², supporting 3D structures and along parallel transects taken at 3-4m distance from the seafloor with both nadiral (camera lens pointing perpendicularly to the ground) and oblique (camera lens pointing to the subject at an angle) shots.

Underwater operations are typically conditioned by dive time (or depth), high logistical costs, varying environmental constraints (water clarity, current, swell) and lack of positioning information. We therefore aimed to develop a technique that guarantee a minimum number of images taken at the right distance from the subject in a short amount of time. Our protocol, developed over three years of field work, positions the photographer in a 3D space (water) in a very precise way. The main goal was to take images exactly at the right spot to ensure a longitudinal and lateral overlap grid of 75%, at a constant distance, to maintain the same precision throughout the data acquisition. The increase of the lateral overlap percentage was the best choice in terms of reconstruction, deployment, time spent underwater, and possible route deviation.

1.5 Georeferencing and scaling

GCPs (ground control points), made with small aluminium squares painted over with a checkerboard pattern, were used to georeference the subject. XY GPS coordinates were obtained from a Garmin field GPS over each GCP location (WGS84 coordinate system) using a surface buoy system deployed from the seafloor at the end of the photographic acquisition. The Z coordinate, depth, was taken one before and one after the photographic acquisition from a dive computer (Aqualung i300 depth gauge, in meters with one decimal). For isolated coral colonies, no GCP were used. As for reefscapes, GCPs were positioned homogeneously in terms of surface coverage and depth (minimum and maximum), one at each corner of the area (total of four), and at least four more within the study site.

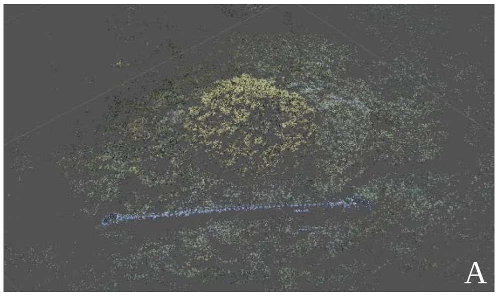
Aluminum scale bars of known size painted with a checkerboard pattern were used for scale. For isolated coral colonies, only one scale bar was placed close to the subject. For reefscapes and artificial structures, one scale bar was placed in the center and two at opposite borders of the study site to ensure no reconstruction deviation. All GCPs and scale bars were photographed and used in the reconstruction of 166 datasets acquired for this study.

1.6 2D and 3D reconstruction workflow

Each of the 131 coral colonies were processed using Metashape Professional version 1.5 (Agisoft 2019) in the following sequence: estimate quality of each image, align images, generate sparse cloud (Figure 3.A), scale, build dense cloud (Figure 3.B), build mesh model (Figure 3.C), build texture, and export supports. Coral colonies were cleaned (isolated) from non-relevant parts of the reconstruction such as the seafloor and artifacts and filled using Metashape close holes tool (Figure 3.D) to build an entire closed 3D object. Since our study on coral colonies focuses on accurate measurements of lengths, surfaces, and volumes, we chose the Metashape Professional (Agisoft 2019) software given its affordable cost, its user-friendliness, alignment algorithm suited for oblique “free flight” shots, the quality of mesh reconstruction, reduced processing time, and more appropriate dedicated tools compared to other software.

For each reefscape and artificial structure, we first used a color chart placed on the study site to be able to adjust light, contrast, sharpness, and colors of images in Lightroom Classic CC version 8.1 (Adobe, 2018) since the water column filters colors according to depth. Once adjustments were made, the sites were processed using Pix4D Mapper Pro version 4.2.26 (Pix4D, 2018) as follows: we aligned images, generated a sparse cloud, georeferenced and scaled the images, optimized camera settings, built a dense cloud, built a DEM (Digital Elevation Model), built an orthoimage, and exported supports. Since our study on reefscapes and artificial structures focused on measuring slope, rugosity, and change over time, we chose Pix4D Mapper Pro (Pix4D, 2018) as it provided a better alignment algorithm on nadiral shots and optimal results for both DEM and orthoimages.

All computer processing was carried out with various settings but at least i7 8th generation or i9 multi-core Intel CPU (Intel, 2018, 2019), SSD disks, 32 or 64Gb of RAM and a GTX1060/1080 GPU (Nvidia, 2016) with CUDA.



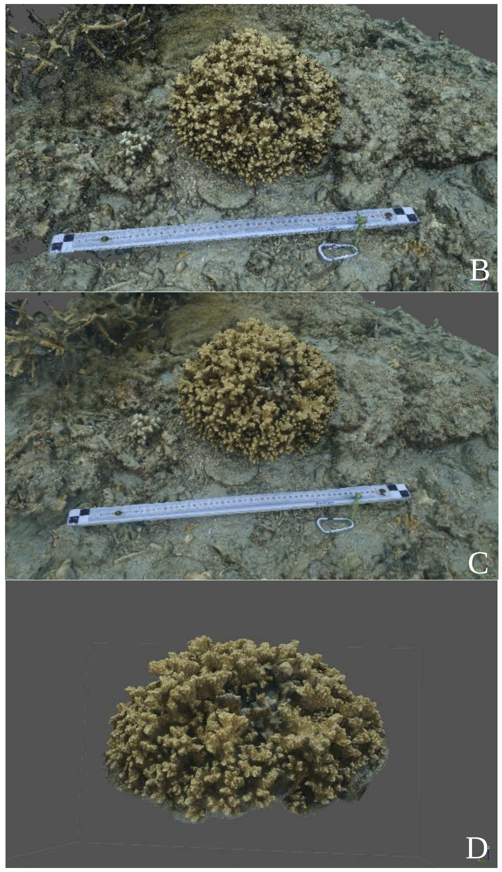


Figure 3. 3D reconstruction workflow of a coral colony

2. Results

2.1 Accuracy and error

The two photogrammetric softwares have a rather similar range of error for mean values, while image alignment is better when using Metashape Professional (Agisoft 2019) and spatial error reprojection is best with Pix4D Mapper Pro (Pix4D, 2018) (Burns, Delparte, 2017). Others also assessed accuracy and error on the same topic (Burns et al., 2015a, b, 2016, 2017; Figueira et al., 2015; Guo et al., 2016; Casella et al., 2017; Mizuno et al., 2017; Marre et al., 2019). Further, Niederheiser et al. (2016) found minor variations when comparing the two softwares for 3D terrestrial reconstructions.

During our calibration tests, when compared to reality, measurements of the underwater 2D and 3D reconstructed supports were equivalent to within +/- 1mm, the smallest measurable distance and level of accuracy used here.

In terms of positioning, each of the XY coordinates were accurate within 3-5m in absolute, depending on the GPS reception, number of satellites received by the GPS device. The Z coordinate (depth) was accurate to within 0.1m as stated in the computer user manual (Aqualung, 2015).

2.2 Relative and absolute precision

Based on the GSD formula, reconstructions of coral colonies had a relative precision of 0.2mm/pixel due to the distance of acquisition from the subject which was approximately 30cm. Reconstructions of reefscapes and artificial structures had a relative precision of about 0.8mm/pixel given that photographs were taken approximately 3m from the seafloor.

2.3 Technical visual tool

Compared to standard methods such as multi-beam imagery that present a point cloud visualization with a color gradient, outputs from photogrammetry, especially 3D mesh models, provide undeniable high visual contents. Those reconstructions offer decision-making technical tools for feasibility studies (site selection) and implementation of monitoring methods.

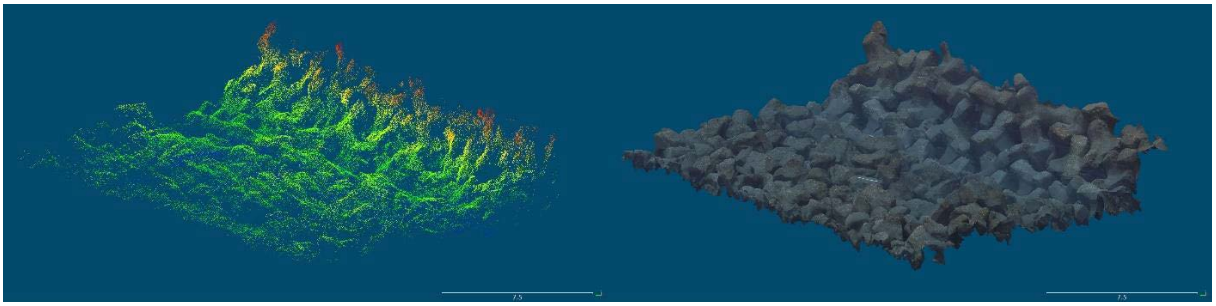


Figure 4. Multi-beam (right) and photogrammetric (left) visualizations

2.4 2D and 3D characteristics extraction

We extracted 3D characteristics of coral colonies by measuring 3D lengths, surfaces, and volumes on mesh models using Meshlab version 2016-12 (Meshlab, 2016). We also made planar surface measurements (projected area) on the orthographic reprojections using spatial analysis tools of Global Mapper version 19 (Blue Marble Geographics, 2017) and diameter calculation using the minimum enclosing circles tool of QGIS version 3.4.6 Madeira (Open Source Geospatial, 2019).

For reefscapes, we measured slope and multiple profile rugosity with the path profile tool and surface rugosity with the cut and fill tool of Global Mapper version 19 (Blue Marble Geographics, 2017).

For artificial structures, we used Global Mapper version 19 (Blue Marble Geographics, 2017) to make slope and rugosity measurements (Figure 5) and detect empty spaces and profile outliers with contour lines (Figure 6).

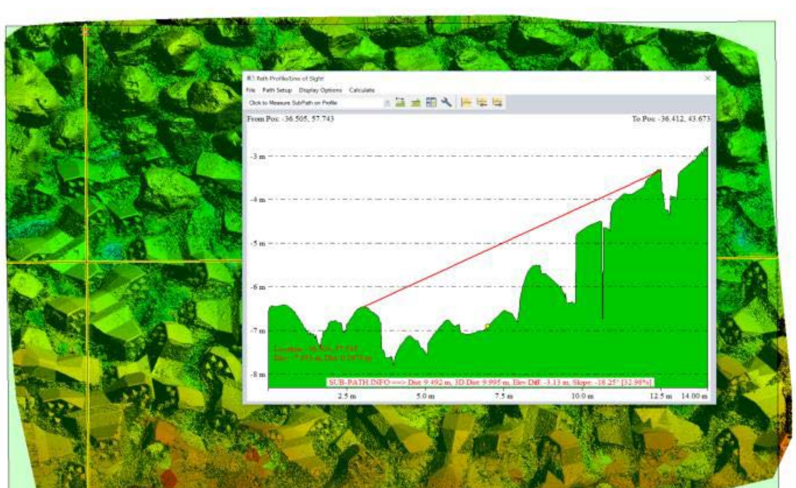


Figure 5. Slope measurement on artificial structure

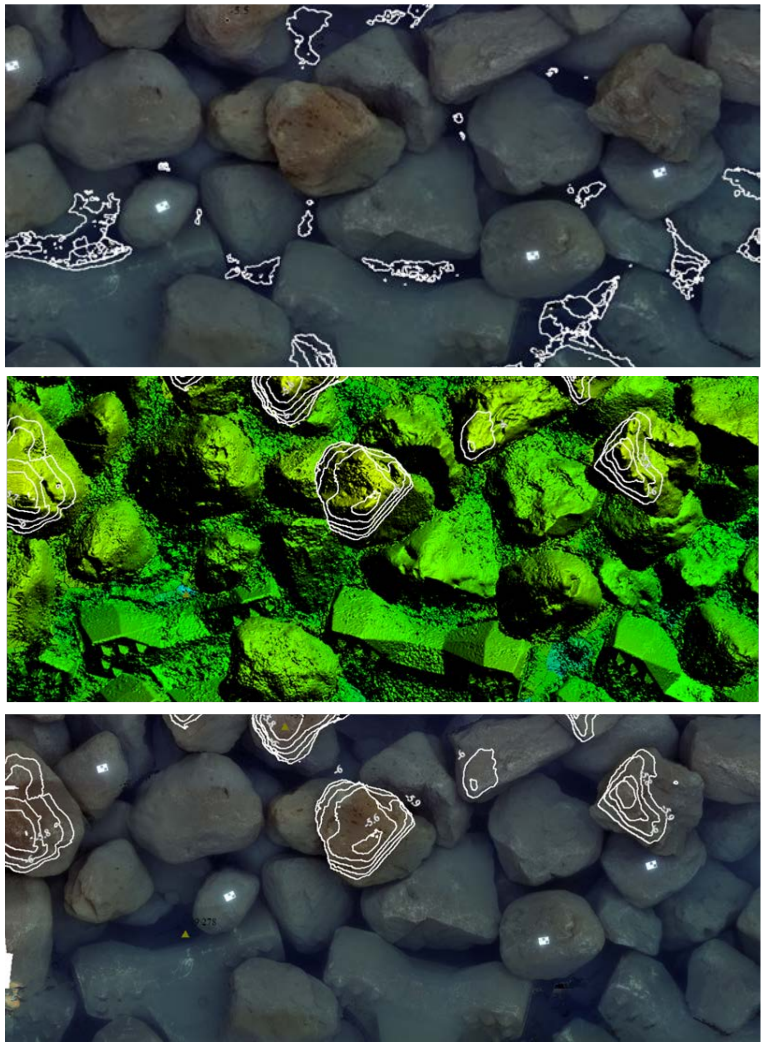


Figure 6. Empty spaces and profile outlier detection

2.5 Time comparison

The ability to compare structure and complexity over time is essential for habitat and structure monitoring and natural resource management. The photogrammetry used here allowed us to compare two models of 3D reconstructions over time acquired within the same study site with CloudCompare version 2.9.1 (GPL software, 2017). For the reefscape, the cloud-to-cloud comparaison of the two models showed an absolute mean difference of less than 0.1mm (Figure 7.B) over the entire site (number of pixels - Gaussian distribution), showing that the protocol is reproductible, except for an object added to the second model (Figure 7.D). The distance between the object and the seafloor was accurately measured as 6.47cm (Figure 7.C). For the artificial structure, we acquired two data sets 6-months apart. By comparing the two models, the cloud-to-cloud comparaison showed movements of rocks resulting from a seasonal swell (Figure 8).

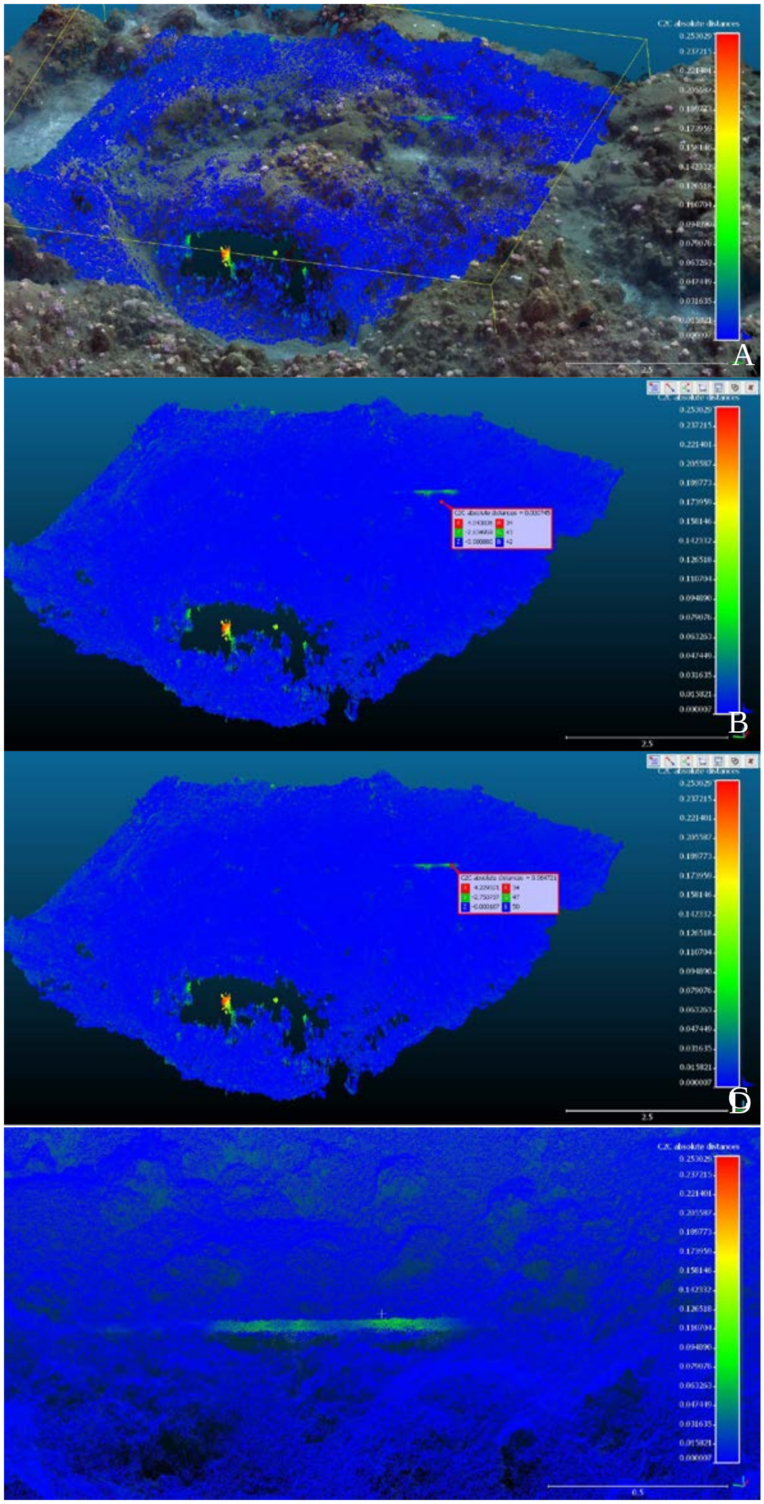


Figure 7. Comparison between two reef seascapes with an added object

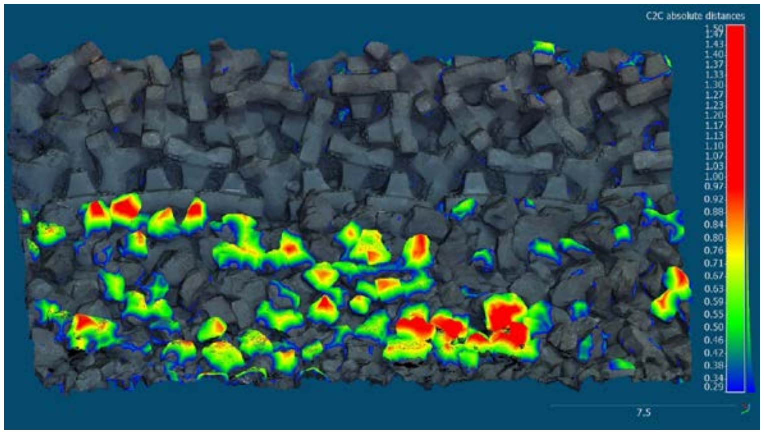


Figure 8. Comparison between two artificial structures with a 6-month gap

Conclusion

Our study aimed to develop specific protocols to accurately reconstruct coral colonies and reefscapes, extend that work to artificial structures and quantify their physical characteristics now and over time. We assessed the best camera configurations, calibrated the changes of underwater photography, and designed two protocols that suit local and global scales. Our entire datasets were reconstructed with a mean resolution of 0.05cm/pixel for 131 isolated coral colonies, 29 contrasted reefscapes and seven artificial structures in shallow water. Accurate 2D and 3D descriptors were extracted from the reconstructions, providing a gain of information, a data bank, and very precise measurements without observer bias leading to a better understanding of 3D complex habitats.

Limitations encountered were mainly associated with the photographic acquisition underwater and the positioning of the images. We could have acquired greater areas with the use of a scuba rebreather to increases the time spent underwater or an automated vehicle (ROV, USV). Further, a USBL transponder coupled with a DGPS on the boat could have provided a better positioning system and enhanced the georeferecing process. Further, the reconstruction and analysis processing time could be reduced using higher performance computer components. Finally, the analytical time spent could probably be significantly reduced by automating the delineations, analysis, and computations using deep learning and auto detection approchs.

The protocols presented here can generate useful and highly accurate environmental indicators to marine resources mangers. This is particularly true when it comes to achieving a better understanding of the long-term influence of structural complexity on ecosystems and associated biodiversity (Urbina et al., 2020).

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