Underwater optical metrology for precision monitoring of marine habitats: the MANATEE project

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Abstract

Marine habitats are subject to monitoring activities to assess the impact of climate change, as required by EU and national directives. Coralligenous reefs are typical Mediterranean underwater seascapes, which originate from the growth of calcareous bioconstructions, including *Lithophyllum stictiforme*, a slow-growing calcareous red algae. The impact of temperature variations on its growth has only recently been investigated in the field, although with destructive sampling methods. The MANATEE (Monitoring and mApping of mariNe hAbitat with inTegrated gEomatics technologiEs) project aims to establish a non-destructive monitoring approach by leveraging geomatic techniques and underwater photogrammetry. The project will test three optical-based systems for divers and on different types of uncrewed underwater vehicles – UUVs (a low-cost micro Remotely Operated Vehicle – ROV and an observation-class UUV). This article presents the experimental procedure to verify that the developed underwater photogrammetry-based method can guarantee the detection of millimetre-level changes per year in the algae growth. A statistically significant number of samples were collected, prepared, and fixed on specially designed tiles and nets featuring photogrammetric targets and placed on the seabed. Following metric traceability principles, control elements (calibrated scale bars and colour checkers) were employed to verify geometric and colorimetric results of underwater photogrammetric surveys. The focus here is on the geometric verification, and the analyses presented demonstrate how the sub-millimetre accuracy potential and reproducibility meet the requirements for *Lithophyllum stictiforme* monitoring.

1. Introduction

The EU enforces marine habitat monitoring (MSFD 2008/56/CE) and Italian directives (D.Lgs. 190/2010) to evaluate the impact of climate change as anthropogenic global warming increases. These directives require standardised survey methods to guarantee comparability across regions and over time.

Among the most vulnerable habitats, coralligenous reefs are characterised by their wide distribution, high biodiversity, and significant role in carbon cycling (Ballesteros, 2006; Martin et al., 2014). Classified in the European Red List of Habitats due to their sensitivity to human pressures (Gubbay et al., 2016; Piazzi et al., 2012), these biogenic formations create complex three-dimensional structures that shelter numerous benthic species, stabilise sediments, and contribute to carbonate production (Ballesteros, 2006).

The main builders of coralligenous frameworks are crustose coralline algae (CCA), slow-growing calcareous red algae that form encrusting bioconstructions (Ballesteros, 2006). Among these, *Lithophyllum stictiforme* (J.E. Areschoug) Hauck (henceforth referred to as *L. stictiform)* is one of the most abundant habitat-building CCAs in Mediterranean coralligenous reefs and plays a crucial role in enhancing local biodiversity (Piazzi et al., 2022). *L. stictiforme* was recently studied for the first time in the field to assess the effects of temperature variations on mortality, growth, reproductive structures, and geochemical composition of the alga (Pinna et al., 2024, 2022)

The MANATEE (Monitoring and mApping of mariNe hAbitat with inTegrated gEomatics technologiEs) project has the primary objective of contributing to the challenge of underwater environmental monitoring, developing protocols based on geomatic techniques (Nocerino et al., 2023). It employs optical-based systems for divers and on different types of uncrewed underwater vehicles – UUVs (a low-cost micro Remotely Operated Vehicle – ROV and an observation-class UUV) to allow measuring sub-centimetre changes in benthic communities, threatened by climate change and anthropogenic stressors (Ventura et al., 2022).

Starting from the study presented in Pinna et al. (2022), within the framework of the MANATEE project, we are currently developing an experimental protocol to assess the effectiveness of optical-based monitoring procedures to estimate *L. stictiforme* growth in situ. In contrast, the experiments designed

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in (Pinna et al., 2022) require that specimens or thalli of *L. stictiforme* be removed from their environment, air dried, embedded into epoxy resin mould, and then sliced using a circular rock saw to measure their growth. To guarantee that sub-centimetre/year changes in *L. stictiforme* specimens are detected underwater, a photogrammetry-based approach inspired by optical metrology practices is designed.

In this contribution, we present the developed experimental protocol and assess the accuracy potential of underwater photogrammetry for *L. stictiforme* growth estimation. The remaining part of the manuscript is organised as follows: First, the MANATEE project is introduced, followed by an overview of related works. We then focus on the designed experimental protocol and discuss the achieved results. Finally, the following steps within the MANATEE project timeline are outlined.

1.1 The MANATEE project

The MANATEE (Monitoring and mApping of mariNe hAbitat with inTegrated gEomatics technologiEs) project aims to develop a technological framework to support monitoring practices of vulnerable marine ecosystems, particularly coralligenous assemblages and their foundational species, the *L. stictiforme*. Existing approaches are primarily based on diver-acquired images or invasive approaches entailing manual sampling and non-reversible sample treatments. On the contrary, MANATEE leverages geomatic methods to enable scalable, high-resolution, and non-invasive procedures. The technical implementation involves three complementary platforms, ideally targeting a specific depth range but tested on a common experiment within the project framework.

1.1.1 An integrated photogrammetry system for divers:

The VIP-FROG (visual inertial pressure – FROG, Figure 1 left) system evolves from the original FROG prototype (Menna et al., 2023), designed to guide a diver in the execution of a photogrammetric survey via a real-time visual simultaneous localization and mapping (vSLAM) approach. In contrast to the original configuration, which used two 1.3 MP global shutter cameras with fisheye lenses, the VIP-FROG introduces a new imaging unit comprising three cameras. The stereo pair now employs two MER2-302-56U3C colour cameras, featuring the Sony IMX265 sensor (2048×1536 px, 56 fps, 1/1.8", global shutter CMOS). These cameras are equipped with wide-angle VA-LM12-12MP-1.85MM-F2.0-018-FISH M12-mount fisheye lenses, offering a 185° field of view, well-suited for operations in narrow and turbid underwater environments. A third camera is added, a ME2S-2020-19U3C model with the Sony IMX541 sensor (4504×4504 px, 19 fps, 1.1", global shutter CMOS), paired with a VA-LCM-10MP-06MM-F1.8-110 C-mount 6mm lens optimised for low distortion and high-resolution imaging. VIP-FROG also integrates inertial and pressure sensors into the acquisition pipeline (Menna et al., 2024). These additional data sources aim to support and improve the vSLAM performance. This new configuration is compatible with the existing underwater housing, consisting of polycarbonate cylinders and dome ports to minimise refraction underwater. The modular design of the original FROG platform is maintained, enabling flexible deployment in diver-held or ROV-mounted configurations.

Figure 1. The three platforms developed and tested within the MANATEE project: a professional diver is shown using VIP-FROG (left); the BlueROV2 from BlueRobotics (centre); the Blucy UUV (right). The three images were taken during the experimental activities run within the MANATEE project.

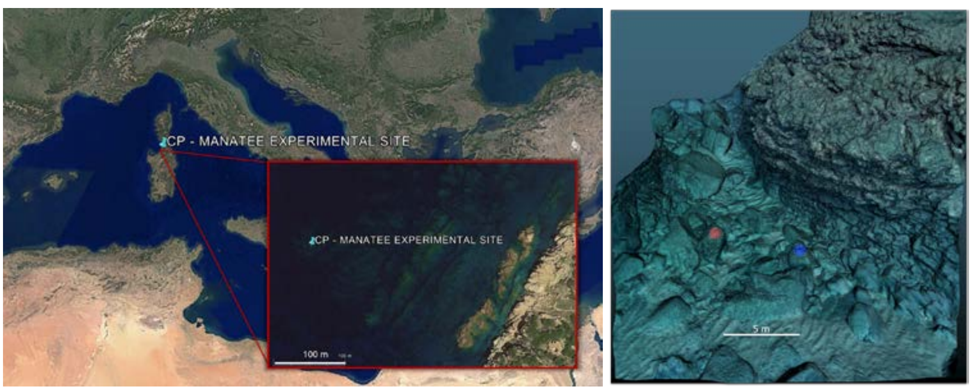

Figure 2. Left: Location of the experimental site selected for the MANATEE project off the Costa Paradiso – CP coast in Sardinia, Italy (GoogleEarth®). Right: 3D model of the CA experimental site[1]. On the right, the wall where the *L. stictiforme* thalli were collected and, on the seabed, the red and blue hotspots where the experiments were placed are visible.

[1] https://geoss.altervista.org/costaparadiso/

1.1.2 A low-cost micro-ROV: It is built upon the BlueROV2 platform[2], a customisable and versatile underwater vehicle used in research, inspection, and environmental monitoring for its stability, manoeuvrability, and modular architecture. Among the available open software and hardware solutions, the BlueROV2 has become very popular within the scientific and professional community as it allows the realisation of relatively complex projects (von Benzon et al., 2022). In its standard equipment, the BlueROV2 is fitted with six thrusters, a forward navigation camera for real-time video feedback to the operator, and navigation instruments, i.e., a depth sensor for vertical positioning and a magnetic compass for heading detection. Its lightweight and compact design allows easy transport and deployment from small platforms, like rubber boats. Once deployed, the ROV can maintain a stable depth autonomously during the mission. In MANATEE, the BlueROV2 (Figure 1 centre) is further equipped with:

- A stereo camera system composed of two GoPro Hero 11 cameras, synchronised via a smartphone-controlled remote system (Del Pizzo et al., 2024);
- A Sony IMX541 industrial camera with a 1.1” CMOS sensor of 1.1” paired with a 12mm focal length lens managed by a Raspberry Pi is enclosed in a custom-designed underwater housing.

While the stereo camera primarily serves to derive a coarse model of the area of interest and scale it, the high-resolution camera is intended to provide higher resolution details, similar to the setup for VIP FROG (section 1.1.1).

1.1.3 An observation-class UUV: developed under the SUSHI DROP (SUstainable fiSHeries wIth DROnes data Processing) project, Blucy (Figure 1, right) is a multi-purpose UUV (Lambertini et al., 2022). Its design supports dual operational modes: tethered ROV mode for pilot-controlled inspection and untethered AUV (Autonomous Underwater Vehicle) mode for autonomous survey missions. Blucy’s onboard navigation suite integrates multiple sensors (GNSS-aided inertial unit, fibre-optic gyroscope – FOG, a Doppler velocity log – DVL) via an Extended Kalman Filter (EKF). An Ultra-Short Baseline (USBL) acoustic link, a downward-facing altimeter (single-beam sonar), and a mini CTD probe (conductivity, temperature, depth) complete the navigation equipment. A forward-facing PilotCam provides live HD video and still imagery for piloting and immediate inspection. Blucy carries a suite of scientific sensors to perform high-resolution mapping and monitoring of benthic habitats, including a multibeam echosounder (MBES) and a downward-looking BottomCam (Nikon Z6 mirrorless with 24 mm lens) dedicated to photogrammetric surveying. Handling Blucy requires a boat with a suitable crane for deployment.

1.2 Paper contribution

This work discusses the experimental design to validate the geomatic approach proposed within the MANATEE project and systematically evaluate the three underwater monitoring platforms presented above. Great emphasis is placed on designing an experiment that follows metric traceability principles to validate the achieved accuracy. Our set-up includes control elements, such as calibrated scale bars and colour checkers, to verify geometric and colorimetric results. Here, we focus on the geometric aspects of the analysis, leaving the in-depth study of colour to be addressed in future work.

2. Related works

Coralligenous reefs have been extensively studied (Ferrigno et al., 2024), and various protocols have been developed to evaluate their ecological status at different depths (Cánovas-Molina et al., 2016; Cecchi et al., 2014; Enrichetti et al., 2019; Gatti et al., 2015; Piazzi et al., 2023; Pinna et al., 2021). Being habitats susceptible to local and global stressors, continuous monitoring is essential to detect signs of degradation, assess the impact of climate change and human activities, and develop effective conservation strategies. Currently, coralligenous reef monitoring employs primarily underwater photographic sampling: single snapshots, randomised in space and time, are processed with image-analysis software to quantify the percentage cover of taxa/morphological groups (Gennaro et al., 2020). On the other hand, to study the effects of stressors on individual species, destructive sampling methods are often employed (Gómez-Gras et al., 2019; Pinna et al., 2024, 2022; Ragazzola et al., 2012), which directly impact the habitat.

Underwater photogrammetry has become a widely adopted technique for coral reef surveys and monitoring in temperate and tropical seas, traditionally performed by SCUBA divers using handheld cameras or rig systems (Remmers et al., 2024). Diver-based surveys can produce accurate, high-resolution 3D models of reef structure (Nocerino et al., 2020). However, human factors inherently limit this approach in depth and duration; although a few examples of scientific expeditions entailing professional saturation diving procedures at high depths exist[3], UUVs offer an effective alternative for surveying activities beyond typical diving depths (~30 m) and in hazardous or remote environments, thus contributing to expanding the scope of underwater research (Paterson et al., 2024), in general, and photogrammetry, in particular. A recent work compared photogrammetry-derived 3D seabed reconstructions obtained from diver and micro-ROV surveys (Paterson et al., 2024). The authors suggest that a hybrid multiscale approach would be beneficial: utilising ROVs for large-scale monitoring and divers for higher resolution products for areas with highly complex and nuanced-scale morphologies (like coralline algae reefs). While this solution may be feasible in shallow water, for mapping and monitoring marine ecosystems at greater depths, UUVs represent the only practicable solution, enabling 3D mapping of benthic ecosystems that were previously inaccessible. For example, Price et al. (2019) used an ROV to collect video transects at nearly 1000 m depth. Imagery data was processed via photogrammetry to obtain a fine-scale rugosity measure of the cold-water coral reef, confirming the critical role of structural complexity in community dynamics.

Compared to the literature, MANATEE aims to test non-invasive approaches based on geomatic techniques, particularly underwater photogrammetry, as alternative methods for assessing the structural evolution of the coralligenous reef bio-constructor *L. stictiforme*. In the following, this paper describes the experimental procedure designed to verify the applicability of our proposed approach.

[2] https://bluerobotics.com/store/rov/bluerov2/

[3] https://medtrix.fr/expedition-gombessa-5-planete-mediterranee-une-mission-scientifique-dans-la-zone-crepusculaire/

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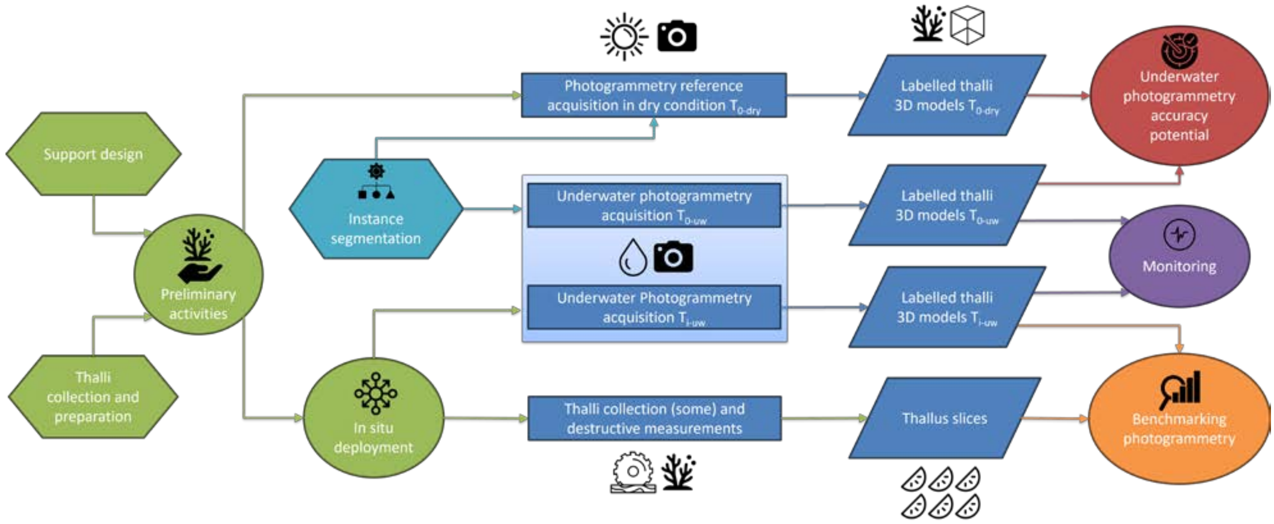

Figure 3. The designed workflow to assess the potential accuracy of underwater photogrammetry for estimating *L. stictiforme* thalli growth. The focus here is on the part of the procedure that concerns estimating the underwater photogrammetry accuracy potential.

Figure 4. Left: *L. stictiforme* thalli in their original environment: an underwater wall spanning different depths at the experimental site (CP). Centre: Some of the harvested thalli. Right: *L. stictiforme* thalli immersed in a solution of Alizarine, a red stain used to highlight the growth of their calcareous structures over time.

3. Materials and methods

The selected experimental site is off the coast of Costa Paradiso (CP) in Sardinia, Italy (Figure 2), where part of the study described in Pinna et al. (2022) was carried out. CP is situated away from anthropogenic influences such as urban centres, industrial facilities, aquaculture operations, and ports. The coralligenous formation of the study area spans depths of 15 to 40 m and is mainly built up by massive calcareous structures dominated by red crustose coralline algae (Pinna et al., 2021). This coralligenous assemblage displays clear zonation patterns, which appear to be driven by biogeographical factors (Piazzi et al., 2021) and particularly by thermal shifts during the summer months (Ceccherelli et al., 2020). Figure 3 outlines the MANATEE experimental design, which is detailed in the following sub-sections.

3.1 Preliminary activities

The number of replicas, i.e., *L. stictiforme* thalli, to perform the multi-temporal analysis was established to ensure statistical significance of the obtained results. For this specific experiment, 30 thalli were collected from a wall in the experimental site at varying depths by SCUBA divers and subsequently immersed in a solution of Alizarine, a red stain used to highlight the growth of their calcareous structures over time (Figure 4). Next, each thallus was fixed on granite tiles, specially designed for the experiment, and equipped with four coded photogrammetric targets (Figure 5 left). The targets serve a multi-purpose function, acting as a scale reference and supporting the metric verification of co-registration between different survey epochs.

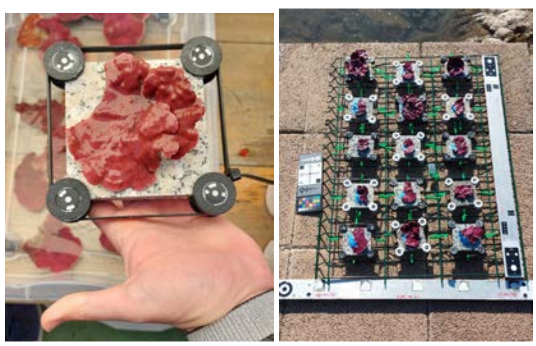

Figure 5. Left: A *L. stictiforme* thallus stained with Alizarine and fixed on a granite tile featuring four coded photogrammetric targets. Right: 5x3 tile grid before installation underwater.

Once prepared, the tiles were secured on two electro-welded nets (Figure 5 right) and measured in dry condition, i.e., in air, by photogrammetry. Calibrated scale bars and colour checkers were concurrently shot in the image acquisition to serve as reference measurements (see section 3.2). The nets with the tiles were then anchored on ad-hoc placed pillars to a depth of about 38 meters on the seabed. This setup should provide durability of the experiment installation throughout the monitoring period (about one year). The tiles were then measured via underwater photogrammetry by SCUBA divers, using the same calibrated scale bars and colour checkers for reference measurements. The image acquisition of the underwater installation was again repeated two weeks later by SCUBA divers (see section 3.3).

3.2 The reference photogrammetric survey in dry condition ($T_{0\text{-dry}}$)

The grids with the thalli were measured in dry conditions with a DSLR Nikon D700 equipped with a 50 mm lens. A redundant photogrammetric network of about 100 oblique and nadir-looking photos with an average GSD better than 0.15 mm was realized. Metric and colorimetric control elements (ten known lengths on two 1 m long scale bars and a colour checker) were simultaneously imaged. Images were colour corrected using the available colour checker, thus defining a baseline to estimate subsequent changes in the colour of the thalli quantitatively. This parameter can be important from an ecological perspective for assessing the evolution of their health status. The network was processed following a self-calibrating bundle adjustment (BA) procedure in Agisoft Metashape[4] using both natural features and the coded targets visible on the tiles. The BA provided a final RMS reprojection error of 0.5 pixel (>0.1 pixel on the targets) and a length measurement error (LME) better than 0.1 mm. A mesh model of the entire grid was created at a resolution of about 0.25 mm; masks were automatically generated using the process described in section 3.4, and models of the individual thalli were produced. These models serve as a geometric reference to assess the potential accuracy of subsequent underwater surveys.

3.3 Underwater photogrammetric surveys ($T_{0\text{-uw}}$ and $T_{1\text{-uw}}$)

The underwater surveys presented in this contribution were carried out with an underwater photogrammetry system independent from those investigated in MANATEE (sections 1.1.1, 1.1.2, 1.1.3). The system is composed of an Olympus OM-D E-M1 II micro four-thirds (MFT) 20MP mirrorless camera mounting an Olympus 9-18mm (18-36 full frame equivalent) zoom lens set at 9mm sealed in an underwater housing, Olympus PT-EP14, with an AOI optical glass dome port. This system had been extensively tested by the authors and will serve as a reference for subsequent underwater surveys realised with the MANATEE platforms.

3.3.1 $T_{0\text{-uw}}$: A first underwater survey was conducted soon after deploying the grids underwater. Control elements, i.e., scale bars and colour checker, were positioned in the scene. About 200 images were acquired with an average GSD better than 0.2 mm and processed in a self-calibrating BA in Agisoft Metashape. Given the use of a dome port whose centring was verified by the authors, the effect of refraction was neglected. The resulting RMS reprojection error and LME were 1.5 pixels (>0.5 pixels on the targets) and better than 0.25 mm, respectively. 3D mesh models of each thallus were derived at an average resolution better than 0.5 mm.

3.3.2 $T_{1\text{-uw}}$: After about two weeks, two underwater surveys were carried out at 24-hour intervals, referred to as $T_{1.1\text{-uw}}$ and $T_{1.2\text{-uw}}$. The second survey was executed after the micro-ROV inadvertently impacted one of the grids during its movement. This event provided an opportunity to assess the effectiveness of the developed procedure in identifying macroscopic changes in the grid structure and demonstrating how the registration of individual tiles is performed using the four visible targets. The imagery datasets of both surveys comprised about 100 images with a GSD better than 0.2 mm and resulting self-calibrating BA processes with an RMS reprojection error of about 2 pixels (>0.7 pixel on the targets) and LME better than 0.5 mm.

3.4 Instance segmentation of *L. stictiforme* thalli

Instance segmentation involves detecting and segmenting each object instance at the pixel level in an image. In our study, the instances to segment are the *L. stictiforme* thalli visible in the photogrammetry imagery datasets in different conditions (dry and underwater) at different epochs. For this task, we employed Roboflow[5], an online platform that provides a suite of tools for building and deploying computer vision models. We manually labelled about 200 *L. stictiforme* thallus instances in 20 images extracted from the $T_{1.1\text{-uw}}$ dataset. After augmentation to increase the diversity and size of our training dataset, the labelled images were split into the canonical train (42 images), validation (4 images), and test (2 images) sets. A custom model based on YOLOv8[6] was trained, providing a mean average precision mAP50-95 of 0.83 and a recall of 0.94. The trained model was applied to the remaining acquired images from all the surveying epochs, and the obtained image masks were used within the photogrammetric processing to segment the individual thalli.

4. Results

The analyses for one of the two grids are shown below. The obtained results are comparable to those obtained for the second grid.

4.1 $T_{0\text{-uw}}$ vs $T_{0\text{-dry}}$: underwater photogrammetry accuracy assessment

Figure 6 shows the residuals of the 6 degree of freedom (DOF) Helmert rigid transformation from T0-uw to T0-dry estimated on 60 targets (four for each tile) on the entire grid. No scale factor was estimated as the two surveys were independently scaled using the calibrated scale bars. As expected, the grid deformed when placed underwater, predominantly in the Z-direction, with a maximum deflection greater than 25 mm. Such deformation would prevent direct comparison, so the individual thalli can only be compared after a local transformation is estimated on the four targets visible on the respective tile. To assess the potential accuracy of the underwater survey, an iterative closest points (ICP) procedure was applied to obtain a fine alignment between the two models. Figure 7., on the left, reports the differences between the two surveys' 3D mesh models of the same thallus. The sub-millimetric difference (standard deviation of 0.3 mm) provides an estimate of the accuracy potential of the underwater photogrammetric protocol.

[4] https://www.agisoft.com/

[5] https://roboflow.com/

[6] https://yolov8.com/

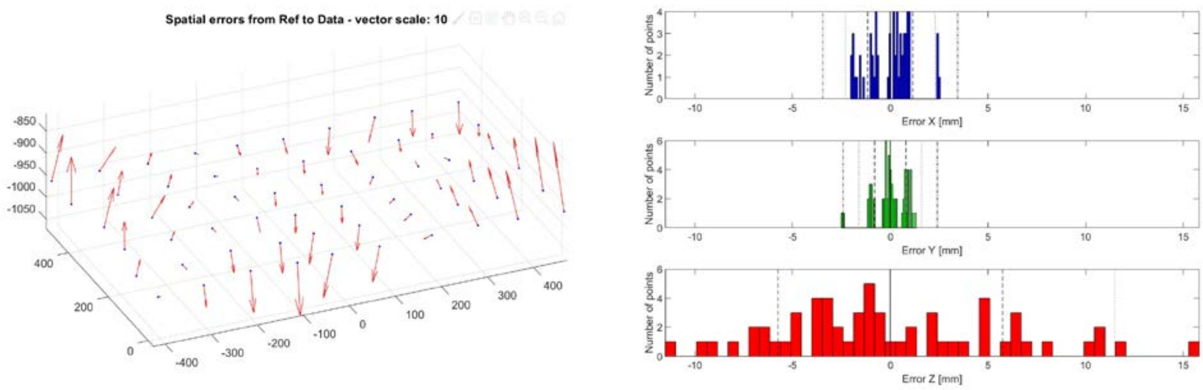

Figure 6. Residuals of the 6 DOF Helmert rigid transformation from $T_{0\text{-uw}}$ to $T_{0\text{-dry}}$ estimated on 60 targets (four for each tile) on the entire grid in mm. Left: spatial vectors (magnitude increased 10 times) display a torsion in the grid shape. Right: residuals in the X, Y, Z components show that the most significant deformation occurred in the Z direction.

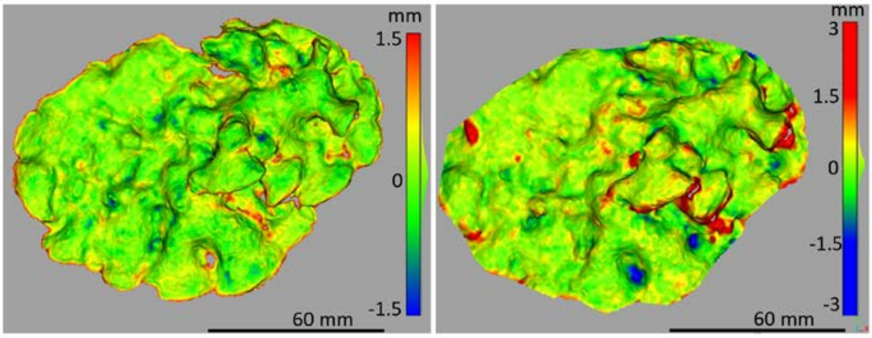

Figure 7. Differences in mm between the 3D mesh model of the same thallus from $T_{0\text{-uw}}$ to $T_{0\text{-dry}}$ (left, after ICP) and from $T_{1.1\text{-uw}}$ to $T_{0\text{-uw}}$ (right, no ICP) computed with the Cloud/Mesh distance tool in CloudCompare[7].

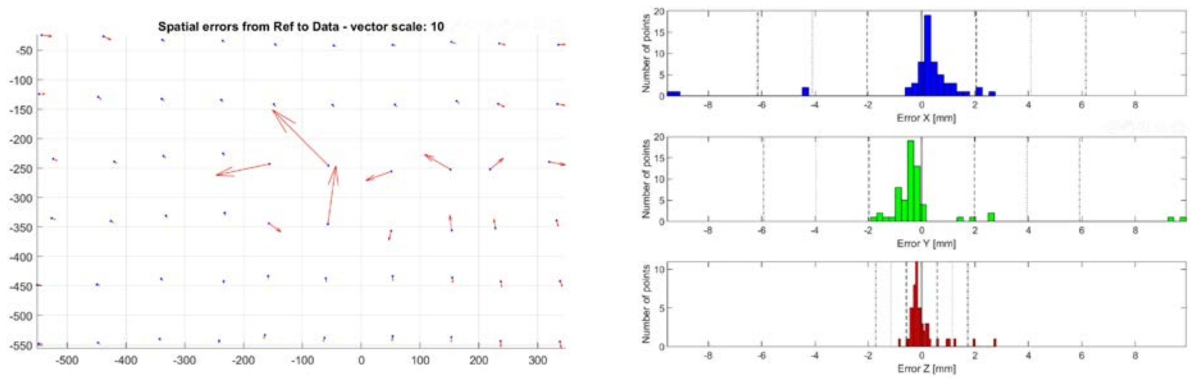

Figure 8. Residuals of the 6 DOF Helmert rigid transformation from $T_{1.2\text{-uw}}$ vs $T_{1.1\text{-uw}}$ estimated on 60 targets (four for each tile) on the entire grid in mm. Left: spatial vectors (magnitude increased 10 times) display rotation in the horizontal plane of the central tile and the tiles to its right, caused by the accidental ROV impact. Right: residuals in the X, Y, Z components show that the most significant deformation occurred in the X direction.

4.2 $T_{1.1\text{-uw}}$ vs $T_{0\text{-uw}}$: set-up stability and underwater photogrammetry reproducibility

The 6 DOF Helmert rigid transformation between the two underwater surveys taken two weeks apart provided the following RMS residuals: RMS_X = 0.2 mm, RMS_Y = 0.2 mm, RMS_Z = 0.4 mm. These values demonstrate the stability of the experimental set-up. The 3D models of the same thallus shown in section 4.1 were compared between $T_{1.1\text{-uw}}$ and $T_{0\text{-uw}}$ to assess the reproducibility of the underwater surveying procedure. In this case, the alignment was estimated based on the targets and was not further refined. The average difference between the models of the two epochs was 0.1 mm, with a standard deviation of 0.45 mm.

4.3 $T_{1.2\text{-uw}}$ vs $T_{1.1\text{-uw}}$: sensitivity to global deformation

The residuals of the transformation show the effect of the ROV's impact on the grid (Figure 8). This caused a significant shift in the X-axis and rotation in the horizontal plane of the central tile and the tiles to its right.

[7] https://www.danielgm.net/cc/

5. Discussion and conclusion

This contribution introduced the MANATEE project, which seeks to develop geomatic tools for the effective monitoring of vulnerable marine environments. It focuses on the *L. stictiforme*, a crustose coralline alga that plays a foundational role in the structure and biodiversity of Mediterranean reef systems. Current practices for studying the evolution of *L. stictiforme* involve taking, manipulating, and finally destroying the samples. Within Manatee, we explore the feasibility of non-invasive monitoring approaches based on geomatic techniques using optical-based systems for divers and different UUVs. For this purpose, we developed an experimental protocol, which involved sampling and preparing 30 *L. stictiforme* thalli. These were placed on tiles equipped with photogrammetric targets and secured to wire meshes positioned underwater. Meshes, tiles, and thalli were measured in dry conditions with photogrammetry, including geometric and colorimetric references. In this preliminary study, a comparison was made with the underwater model obtained just after the grids were laid. The RMS of the differences was found to be 0.3 mm, which indicates that photogrammetry may be suitable for measuring the expected growth of a few millimetres per year. We repeated the comparison after two weeks and obtained measurement reproducibility better than 0.5 mm. This confirmed the possibility of estimating changes over time in the order of millimetres. In addition, we have confirmed the value of the targets' presence on the grids in identifying macro changes between monitoring epochs. This was evident following the unintentional impact of the micro-ROV. As part of the monitoring procedure, instance segmentation proved to help segment the individual thalli. However, we noticed that the masks were cropped by the initial bounding boxes. We are currently looking into a solution to improve the mask output.

Here we focused on setting up the experiment and developing the validation and comparison procedure during the first acquisition campaign. In the next campaign the three platforms, i.e. VIP-FROG, BlueROV2 and Blucy, will be operational. Their output will be analysed based on the results here presented to outline effective monitoring practices. At the end of the experimental period, each thallus will be recollected from the field, transported to the laboratory, and sliced to measure its growth (Pinna et al., 2022). This measure will be a benchmark to validate the growth estimates derived underwater with photogrammetry. Future analyses will also focus on the colour fidelity of the photogrammetry products. This will allow possible correlations between thallus colour variations and health conditions (bleaching) to be assessed.

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