

An action-camera based stereo system for microROV for monitoring coralline algae in the Mediterranean Sea: preliminary assessment

Silvio Del Pizzo
*Dept. of Science and Technology
Parthenope University of Naples
Napoli, Italy*
silvio.delpizzo@uniparthenope.it

Erica Nocerino
*Dept. of Social Sciences and
Humanities
University of Sassari
Sassari, Italy*
enocerino@uniss.it

Salvatore Gaglione
*Dept. of Science and Technology
Parthenope University of Naples
Napoli, Italy*
salvatore.gaglione@uniparthenope.it

Alessio Calantropio
*Dept. of Social Sciences and
Humanities
University of Sassari
Sassari, Italy*
acalantropio@uniss.it

Fabio Menna
*Department of Chemical, Physical,
Mathematical and Natural Sciences
University of Sassari
Sassari, Italy*
fmenna@uniss.it

Salvatore Troisi
*Dept. of Science and Technology
Parthenope University of Naples
Napoli, Italy*
salvatore.troisi@uniparthenope.it

Abstract— Underwater monitoring and surveying are fundamental activities spanning various fields, each contributing significantly to managing marine environments. These activities are crucial in marine ecology, providing essential conservation, management, and research data. The importance of underwater monitoring extends to several key areas, including marine ecology, environmental science, archaeology, and resource management. In marine ecology, monitoring activities are crucial for conserving biodiversity, assessing habitat health, understanding the impacts of climate change, and mitigating human impacts. Stereo-vision systems can be decisive for several underwater activities, such as monitoring, research, and exploration. Commercial stereo-vision systems often involve high costs and complex setups, which limit their accessibility. The proposed approach leverages the affordability of action cameras to create an accessible and effective solution. Indeed, this paper presents the design, implementation, and preliminary testing of a low-cost stereo-vision system utilizing two GoPro 11 for underwater applications on a micro ROV. The design process involved synchronizing two action cameras and developing a mounting rig to ensure a stable relative position between the cameras. The stereo system is calibrated in-air and underwater to test different calibration strategies. The obtained performances will guide practical considerations on using the low-cost, off-the-shelf stereo system based on action cameras for monitoring challenging underwater environments.

Keywords—*Photogrammetry, Underwater, Stereo-camera, Action-cam, MANATEE project*

I. INTRODUCTION

Underwater photogrammetry is recognized as an established key tool in several application fields, including marine science, archaeology, and environmental monitoring [1, 2, 3, 4]. Using images, photogrammetry can deliver accurate and detailed three-dimensional models of underwater environments, providing invaluable data for research, monitoring, conservation, and management efforts [5].

In underwater cultural heritage, photogrammetry has revolutionized the documentation and analysis of submerged sites [6]. Shipwrecks, sunken cities, and ancient artifacts can be surveyed and studied in situ, and necessary excavations can be documented step-by-step. Due to its non-destructive and contactless nature, photogrammetry may preserve the integrity of the sites or document the multitemporal modifications, providing detailed mapping and 3D modeling. Besides being a valuable resource for research, the produced 3D replica can promote conservation planning and public education (i.e., virtual dives and museums), making underwater cultural heritage sites accessible to a broader audience.

Coral reefs, seagrass beds, and other sensitive marine habitats are subject to various environmental stresses due to climate change, pollution, and human activities [7]. Traditional underwater monitoring methods, such as manual surveys and direct measurements, are often time-consuming, labor-intensive, limited in scope, and may involve destructive sample removals. Furthermore, most of them are influenced by the operator's subjectivity [8]. Some of these monitoring tasks can be carried out with photogrammetric techniques, which may allow the acquisition of geometric and colorimetric spatial data over large areas, facilitating the assessment of habitat health, biodiversity, and structural complexity [9]. Environmental monitoring via underwater photogrammetry allows tracking changes over time, such as the progression of coral bleaching events, the impact of coastal development, or the recovery of ecosystems following restoration efforts [10]. By defining baseline data and conducting periodic surveys, researchers can detect trends, identify threats, and evaluate conservation effectiveness by comparing different epochs of different surveys. Despite its many advantages, limitations exist to the ubiquitous application of underwater photogrammetry. Costs of professional, high-quality equipment may be prohibitive; scaling elements, ground truth measurements, and stable features for reference system definition are necessary for obtaining metric results, assessing the achieved accuracy, and

performing monitoring tasks; time underwater is limited for scuba divers, which consequently restricts the duration of photogrammetric surveys. Thanks to its technological advantages, low cost of the Micro Class Remotely Operated Vehicle (ROV) may substitute a diver in this specific underwater task. Indeed, the ROVs can operate in environments that are too dangerous for scuba divers, such as at great depths or in contaminated waters [11]. Moreover, ROVs are not limited to physical endurance or decompression stops, allowing them to operate in deeper environments for longer time. On the other hand, ROVs require skilled operators, support vessels, and teams to manage their deployment and data analysis. Divers could still be preferred in complex environments for their dexterity, flexibility, and problem-solving capabilities [12].

Finally, automatic photogrammetric processing approaches, working both in post-processing after the image acquisition has been finalized or in real-time (e.g., Structure from Motion—SfM, Simultaneous Localization and Mapping—SLAM, and Visual Odometry—VO), have further increased the widespread use of underwater photogrammetry, enabling a broader range of scientists and practitioners to leverage its benefits.

The study presented in this paper was developed within the MANATEE (Monitoring and Mapping of Marine Habitat with Integrated Geomatics Technologies) project [13]. MANATEE aims to tailor photogrammetry-based approaches to assess the accretion or reduction of coralline algae, such as the *Lithophyllum stictiforme*, which form the foundation of Mediterranean coral reefs and whose growth is estimated at a few mm per year [14]. It involves the use of different platforms, from divers equipped with systems capable of guiding the photogrammetric acquisition in real-time to micro ROVs and working-class uncrewed underwater vehicles (UUVs). Here, we discuss the set-up and calibration of a low-cost stereo-vision system based on action cameras (GoPro 11), conceived to provide stereo-capabilities to a micro-ROV employed in underwater environmental monitoring tasks.

Using action cameras for photogrammetric applications, both in air and underwater, in different set-ups (single, stereo, and multi-camera systems) is not a new practice [15, 16, 17, 18, 19]. Several studies have also focused on their quality, accuracy potential, sensor and system synchronization, and calibration [20, 21, 22, 23, 24]. Here, we present a comparative analysis of two different calibration approaches to estimate the relative orientation between the two cameras:

- *A-posteriori approach*: during the bundle adjustment, the image pairs are treated as if they were acquired by two unconstrained cameras. Therefore, the estimated external orientation parameters are processed following a statistical method to define the most probable value of the baseline.
- *Constrained approach*: the image pairs are treated as if they were captured by a synchronized stereo camera system, with the cameras rigidly fixed relative to each other (a camera rig). Their relative orientation is estimated during the bundle adjustment process.

Our emphasis is on the estimation of the baseline to scale the photogrammetric survey without the need to place additional elements of known length into the scene. Therefore, we investigate the possibility of pre-calibrating the system out of the water and using the estimated baseline for the in-water

survey, bearing in mind that our metric accuracy requirements are to monitor species that grow a few millimeters per year.

II. SYSTEM SETUP

This study employed a low-cost platform (BlueROV2) equipped with a stereoscopic camera system (Figure 1). It is designed to enhance underwater data acquisition capabilities. The system setup involves several components, and the following sub-sections will detail the configurations.



Fig. 1. BluROV2 equipped with a Stereo Camera system on the poolside where the experimentation phase was conducted

A. Stereo-camera System

The stereo camera system comprises two high-resolution cameras mounted at a fixed distance on an aluminum bar. Specifically, two underwater camera housings are fixed to the bar with three steel self-locking screws; the tilting movement is locked using a further locking screw located on the base of the mount. Such configuration plays a crucial role in the system's functionality (Figure 2). The camera's baseline is about 25 centimeters long. The system is operational when both cameras are housed. This setup allows for acquiring images with high overlap, an essential requirement for producing 3D scene reconstructions.



Fig. 2. Stereo-camera system composed of two action cameras and their underwater camera housing. The system is held by an aluminum bar.

In this work, two GoPro® cameras version 11 were employed. Each camera was set to acquire a video with a resolution of 4K (3840x2140 pixels). These cameras can

operate at different frame rates; for example, with 4K resolution, they can record 24, 30, and 60 frames per second. The system is designed to be engaged in the front part of the ROV and can be adjusted before the dive to different downward preset inclinations. In this study, the video acquisitions were conducted with the GoPro's video stabilization feature disabled. Such a decision was adopted to preserve the natural perspective of the image frame. Indeed, by disabling stabilization, we ensure that the internal orientation of the camera is retained.

B. Remotely Operated Vehicle

In this research work, a BlueROV2 was employed. This platform is a highly versatile and robust micro Remotely Operated Vehicle designed for various underwater applications. The BlueROV2 has a modular design, allowing users to customize and expand it to meet their needs. This feature makes it appealing for multiple tasks; additional components can be easily added and removed. For these reasons, it is widespread in different scientific fields such as marine biology, geology, and environmental monitoring, especially for exploring hard-to-reach environments and collecting data. [25]

The BlueROV2 uses the ArduSub open-source autopilot system based on the widely used ArduPilot firmware. Control is intuitive, using a gamepad-style joystick that allows precise movements. The control software provides real-time telemetry data, including depth, heading, and orientation, giving operators comprehensive situational awareness.

This vehicle has a high-definition, low-light camera that provides clear recordings even in dimly lit environments. The camera is mounted on a tilt mechanism, allowing the viewing angle to be adjusted easily. Also, powerful LED lights illuminate the underwater scene, improving the quality of the video.

The BlueROV2 is powered by lithium-ion batteries that provide several hours of operational time, depending on payload water temperature and current.

Flexibility is the real strength of the BlueROV2. Indeed, it supports a variety of payloads, such as additional cameras, sonar systems, and manipulators, and it can be adapted to perform different missions. Moreover, it is an open-source platform, and both the hardware and software can be customized by users, encouraging innovation and adaptation to unique needs. Additionally, BlueROV2 is supported by a strong community of users and developers who provide a wealth of resources, support, and shared knowledge.

III. METHODS

Calibration of stereo cameras is an essential process that allows us to obtain 3D models with known scale without any need for positioning scale bars within the surveyed scene. Stereo-camera calibration is a process that calculates both the internal camera parameters of each camera and the external relative orientation between them [26].

However, the operational environment can significantly influence the calibration process, introducing unique challenges and requirements. The synchronization between the two cameras during image acquisition is a critical factor; indeed, if a temporal misalignment occurs, the relative orientation between the cameras cannot be considered constant during the survey. This section outlines the methodologies for calibrating stereo cameras in two distinct

environments: a controlled laboratory setting and a controlled underwater environment.

A. Synchronization

Synchronizing frames from two cameras is crucial in stereo-photogrammetry. Indeed, accurate synchronization ensures that frames from both cameras correspond at the same moments in time, enabling coherent analysis and processing. The main methods utilized for performing the synchronization can be divided into three different categories [27]:

1. **Hardware synchronization.** It is a technique where an external device provides a timing signal to synchronize other devices (slave cameras), or a dedicated trigger generator sends a pulse to both cameras simultaneously. Triggering involves using a common trigger signal to control the frame capture of both cameras. This method ensures that both cameras capture frames simultaneously by locking them to a common external timing signal, often by a pulse-per-second (PPS) signal or a dedicated sync cable. It is widely used in professional video production environments due to its precision.
2. **Software synchronization.** It is a technique that allows synchronization, not by acting on hardware. Two approaches can be defined based on this type of synchronization: time stamps or feature matching based. In the former, each camera records its timestamps for its captured frames. During post-processing, these timestamps align the frames from both cameras. Network Time Protocol (NTP) or Precision Time Protocol (PTP) can synchronize the cameras' internal clocks. This method relies on the accuracy of the camera clocks and network synchronization, which might introduce slight delays or drifts. In the absence of hardware synchronization, feature matching can synchronize frames. This involves identifying common features or events in the video streams from both cameras and aligning frames based on these features. For example, the appearance of a distinctive object (switching on a led) or a clap can serve as a reference point for synchronization. However, these approaches are less precise than hardware-based methods and can achieve an accuracy of 0.5 frames.
3. **Hybrid approach:** Combining hardware and software synchronization methods can enhance accuracy and flexibility. For instance, hardware triggering can be used for initial synchronization, and software-based timestamp correction can compensate for any drift or discrepancies over time. This approach leverages the strengths of both methods, ensuring high precision while accommodating any minor timing variations.

In this work, the synchronization was carried out using hybrid mode. The acquisition command was sent to both cameras through a Bluetooth remote control. Several artificial events, such as specific sounds and light activation, control the synchronization. It is always recommended to perform such checks at the beginning as well as at the end of the survey.

B. Calibration in laboratory

In the first phase, the calibration was performed in the laboratory using a calibration test field composed of coded targets arranged in 3D space and a calibrated scale bar (Figure 3). The GoPro cameras were set to acquire a resolution of 4K and a frame rate of 60 fps.

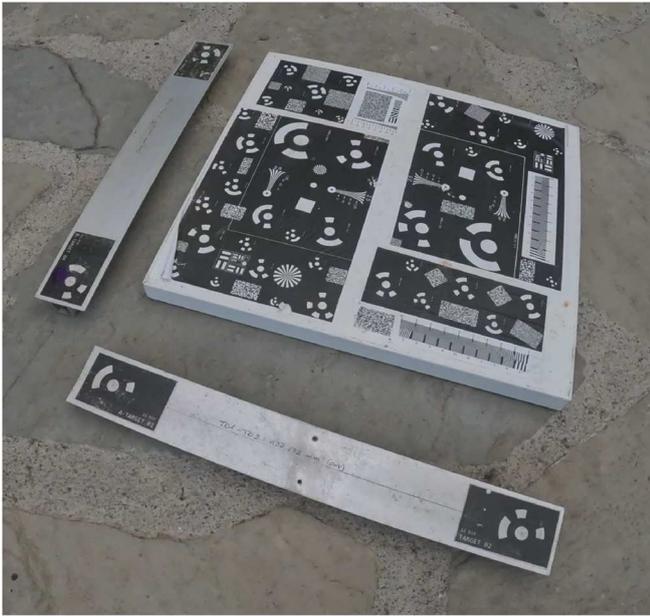


Fig. 3. Calibration test field pattern employed to perform the camera calibration test.

During the acquisition, the operator moved the stereo camera according to the best practice for performing the camera's self-calibration: acquiring the targets on the calibration pattern from different angles, ensuring that the targets are uniformly distributed on the images [28]. The acquisition procedure provided 111 image pairs by extracting one frame every 60 frames.

During the survey, the stereo camera acquired, for several seconds, the screen of a smartphone where a chronometer was started up. Several image pairs were analyzed to estimate the synchronization error. Analyzing the recorded times, no significant differences were detected, considering that the smartphone screen has a refresh rate of 120 Hz (twice as high as the camera's acquisition rate).

In this work, the synchronization error can be estimated as lower than the duration of a frame (0.016 seconds), corresponding to a submillimeter error if the transversal speed component of microROV is lower than 6.2 cm/sec.

C. Calibration in Swimming-Pool

When a camera is used underwater in housings mounting flat ports (like the standard one bundled with the GoPro camera), its internal orientation parameters change significantly compared to its use in the air due to differences in the refractive index between the two media. Refraction impacts various aspects of image capture, including focal length, field of view, and lens distortion, altering the straight path of light rays when passing from air to water. As a result, the camera's effective focal length increases in underwater environments. Moreover, due to the total internal reflection (TIR) phenomenon, the maximum field of view allowed becomes about 97 degrees for an air-to-water interface. A practical effect of the camera calibration model is that the fisheye formulation is no longer needed. Understanding these effects is fundamental in underwater photogrammetry. The choice between a dome port and a flat port influences the effectiveness of this process [29]. There are two types of ports:

- **Dome Ports:** Ideal for wide-angle and general photogrammetry work, where refractive effects introduced by water are minimized. When correctly centered, dome

ports preserve the FOV and, in practice, maintain the in-air distortion profiles. Towards the corners of the image, dome ports introduce aberrations due to Petzval field curvature. They are preferred for large-scale mapping, surveys, and environments where **ample** FOV image clarity and detail are paramount.

- **Flat Ports:** These are less suitable for high-accuracy applications if refraction is not **adequately** modeled, such as when using a classical pinhole camera model. The errors introduced by uncompensated refraction effects become more and more significant as the entrance pupil distance from the flat interface increases. Flat ports reduce the FOV and introduce strong pincushion distortion and chromatic aberrations and are often preferred when budget is a constraint.

Beyond the geometric effects, water also affects image clarity and color. Indeed, water absorbs light more than air, particularly affecting the red end of the spectrum, which can result in images with a blue or green cast. This color shift means that photographers must consider white balance correction and potentially use color enhancement methods to improve radiometric accuracy in the images.



Fig. 4. Underwater camera calibration pattern located on the swimming pool floor.

Although the distance between the entrance pupil and the flat port in the GoPro systems is only a few millimeters, camera calibration in the prevailing surveying conditions is recommended if the application of interest requires high accuracy, as in the case of the aims of the MANATEE project. In addition, the calibration of the stereo system in water is a focus of the current study, as we intend to compare it with the results obtained in-air. The calibration procedure was carried out in a swimming pool, where a calibration fixture and two calibrated scale bars were positioned on its floor (Fig. 4). The acquisition procedure was performed by setting the GoPro cameras in 4K video mode with 60 fps, and 184 images (92 image pairs) were collected.

IV. RESULTS

The calibration experiments realized in a controlled laboratory facility and in underwater (swimming pool) have provided promising results.

For both environments, the photogrammetric processing was carried out in two different ways using Agisoft

Metashape: (i) in free network bundle adjustment with self-calibration of the two cameras using the frame camera model and (ii) relative pose constraints (translation and rotation) of the right camera with respect to the left one on the rig. In the first method, the baseline between the two cameras is estimated a posteriori as the mean of the Euclidean distance between the left and right optical centers. According to the expected mechanical stability and synchronization error between left and right frames, a fixed distance constraint can be given between the two cameras.

Figure 5 shows the results obtained in the laboratory for the image dataset acquired in a dry environment; the mean value is highlighted with the blue line, which is 249.11 mm with a standard deviation of 0.34 mm.

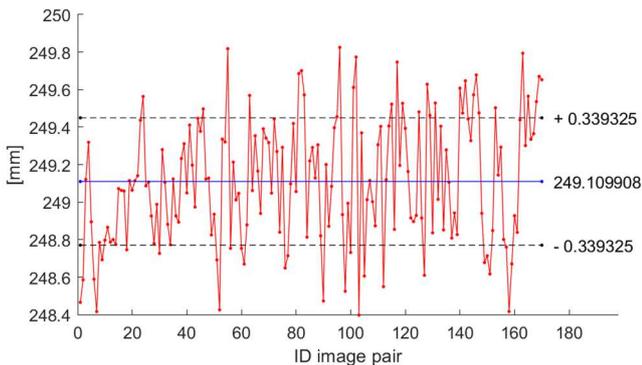


Fig. 5. Baseline distance between the two cameras computed in free-network adjustment in the laboratory, above the water

The same process was performed for the underwater environment with Agisoft Metashape and figure 6 shows the results obtained; the mean value of the baseline is 249.30 mm, with a standard deviation of 0.10 mm.

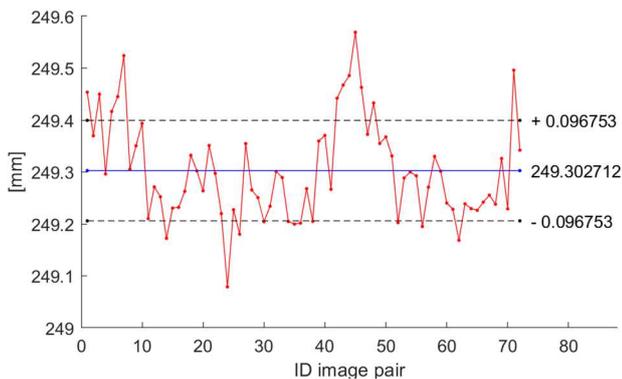


Fig. 6. Baseline distance between the two cameras computed in free-network adjustment underwater

A second elaboration was performed to estimate the baseline value by imposing geometric constraints between two cameras during the Bundle Adjustment. The procedure involves setting up a master camera and a slave camera. The relative orientation will be computed in a reference system centered on the master camera. Of course, the orientation parameters can be adjusted during the process.

Table I reports the baseline estimations using the two approaches for both environments, with the corresponding standard deviations.

The results reported in Table I suggest that despite the combined presence of refractive effects introduced by the flat port and mechanical instability of the rig, there is no significant change between air and underwater calibrations. Calibrating in dry conditions for underwater use has several benefits, particularly for a system to be mounted on a micro-ROV working in free swimming mode. Indeed, in the case of the BlueROV2, it would not be easy to carry and manipulate the test field underwater at the operative depth.

In our tests, we used the calibrated baseline value in dry conditions to scale the underwater survey and simulate a contactless survey where the stereo camera alone can provide metric measurements. The error on the two scalebars about 43cm long resulted of 0.34 mm (relative error better than 1:1000).

TABLE I. STEREO CAMERA RESULTS COMPARISON

		Above water Dataset	Underwater Dataset
Baseline length [mm]	Metashape "Master/Slave"	249.26 ± 0.17	249.12 ± 0.20
	A-posteriori approach	249.30 ± 0.10	249.11 ± 0.34
GSD [mm]		0.3	0.2

V. CONCLUSIONS

This paper introduced a low-cost stereo-vision system based on action cameras designed for underwater monitoring using micro-ROVs. Within the MANATEE project, the ROV will be tasked to map and monitor coralline algae that are estimated to grow a few millimeters per year. Accordingly, the stereo-system must be able to meet the stringent requirements to accomplish the monitoring goal. The focus of this study was to test a calibration procedure able provide scalable 3D reconstructions of marine environments, while assuring an easy implementation.

We presented a comparative analysis of two calibration strategies demonstrated that the differences in the estimated baselines between the two are not statistically significant. Indeed, the variations observed are smaller than the Ground Sampling Distance (GSD) and the standard deviation measured in dry and underwater environments. This indicates that, despite the complexity introduced by the underwater environment, the system can achieve reliable and consistent results. Furthermore, the preliminary results suggest that the stereo-system calibration conducted in dry conditions can be applied to underwater surveys, avoiding repeating the calibration procedure underwater; this is a significant advantage when the system operates in challenging environments using remote vehicles.

Preliminary results are encouraging, showing that the stability of the system may allow to simplify the stereo calibration procedure, i.e. using the values estimated in-air for scaling an underwater survey.

We plan to extend the present study in open water and operational environment, where more challenging conditions, such as varying light, water turbidity, and varying operational depths are expected. Future work will focus on further investigating the robustness of the stereo calibration process

and integrating the stereo camera system with a high-resolution camera, improving its resolution, accuracy and reliability.

ACKNOWLEDGMENT

The authors acknowledge financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU– Project Title MANATEE – CUP I53D23001970006- Grant Assignment Decree No. 961 adopted on 30/06/2023 by the Italian Ministry of University and Research (MUR).

REFERENCES

- [1] G. Marre, F. Holon, S. Luque, P. Boissery e J. Deter, “Monitoring marine habitats with photogrammetry: a cost-effective, accurate, precise and high-resolution reconstruction method,” *Frontiers in Marine Science*, vol. 6, p. 276, 2019.
- [2] P. Drap, J. Seinturier, D. Scaradozzi, P. Gambogi, L. Long e F. Gauch, “Photogrammetry for virtual exploration of underwater archeological sites,” in *Proceedings of the 21st international symposium, CIPA*, 2007.
- [3] P. Rossi, M. Ponti, S. Righi, C. Castagnetti, R. Simonini, F. Mancini, P. Agrafiotis, L. Bassani, F. Bruno, C. Cerrano e others, “Needs and gaps in optical underwater technologies and methods for the investigation of marine animal forest 3D-structural complexity,” *Frontiers in Marine Science*, vol. 8, p. 591292, 2021.
- [4] E. Nocerino, F. Menna, A. Gruen, M. Troyer, A. Capra, C. Castagnetti, P. Rossi, A. J. Brooks, R. J. Schmitt e S. J. Holbrook, “Coral reef monitoring by scuba divers using underwater photogrammetry and geodetic surveying,” *Remote Sensing*, vol. 12, p. 3036, 2020.
- [5] A. Calantropio e F. Chiabrando, “Underwater cultural heritage documentation using photogrammetry,” *Journal of Marine Science and Engineering*, vol. 12, p. 413, 2024.
- [6] J. Henderson, O. Pizarro, M. Johnson-Roberson e I. Mahon, “Mapping submerged archaeological sites using stereo-vision photogrammetry,” *International Journal of Nautical Archaeology*, vol. 42, p. 243–256, 2013.
- [7] J. M. Lough, K. D. Anderson e T. P. Hughes, “Increasing thermal stress for tropical coral reefs: 1871–2017,” *Scientific reports*, vol. 8, p. 6079, 2018.
- [8] C. N. Bianchi, A. Azzola, S. Cocito, C. Morri, A. Oprandi, A. Peirano, S. Sgorbini e M. Montefalcone, “Biodiversity monitoring in Mediterranean marine protected areas: Scientific and methodological challenges,” *Diversity*, vol. 14, p. 43, 2022.
- [9] R. Ferrari, L. Lachs, D. R. Pygas, A. Humanes, B. Sommer, W. F. Figueira, A. J. Edwards, J. C. Bythell e J. R. Guest, “Photogrammetry as a tool to improve ecosystem restoration,” *Trends in Ecology & Evolution*, vol. 36, p. 1093–1101, 2021.
- [10] K. L. Kopecky, G. Pavoni, E. Nocerino, A. J. Brooks, M. Corsini, F. Menna, J. P. Gallagher, A. Capra, C. Castagnetti, P. Rossi e others, “Quantifying the loss of coral from a bleaching event using underwater photogrammetry and AI-assisted image segmentation,” *Remote Sensing*, vol. 15, p. 4077, 2023.
- [11] Z. Hao, P. K. Kaundal, T. Liu, S. R. Mckinlay, S. Ouyang, F. Tang, M. Shavandi e C. Cheng, “Technology Advancement in Deepwater Pipeline Repair to Mitigate Offshore Risk and Application Case Study of Duplex Pipe Recommissioning by ROV Operation,” in *Offshore Technology Conference*, 2023.
- [12] A. J. P. R. Britto, “Subsea Inspections with New Models of Autonomous Underwater Vehicle (AUV): Deployment Modes, Advantages and Disadvantages,” in *Offshore Technology Conference*, 2023.
- [13] E. Nocerino, S. Del Pizzo, A. Lambertini, S. Troisi e L. Vittuari, “MANATEE Project: Monitoring and Mapping of Marine Habitat with Integrated Geomatics Technologies,” in *2023 IEEE International Workshop on Metrology for the Sea: Learning to Measure Sea Health Parameters (MetroSea)*, 2023.
- [14] F. Pinna, A. Caragnano, L. Piazzzi, F. Ragazzola, P. Stipcich, F. Rindi e G. Ceccherelli, “The Mediterranean bioconstructor *Lithophyllum stictiforme* shows adaptability to future warming,” *Frontiers in Marine Science*, vol. 9, p. 930750, 2022.
- [15] M. Ballarin, C. Balletti e F. Guerra, “Action cameras and low-cost aerial vehicles in archaeology,” in *Videometrics, Range Imaging, and Applications XIII*, 2015.
- [16] V. E. Schmidt e Y. Rzhanov, “Measurement of micro-bathymetry with a GOPRO underwater stereo camera pair,” in *2012 Oceans*, 2012.
- [17] M. Koehl, T. Delacourt e C. Boutry, “Image capture with synchronized multiple-cameras for extraction of accurate geometries,” in *XXIII ISPRS Congress (2016-07-12, 2016-07-19: Prague, Czech Republic)*, 2016.
- [18] E. A. Nelson, I. T. Dunn, J. Forrester, T. Gambin, C. M. Clark e Z. J. Wood, “Surface reconstruction of ancient water storage systems an approach for sparse 3D sonar scans and fused stereo images,” in *2014 International Conference on Computer Graphics Theory and Applications (GRAPP)*, 2014.
- [19] T. Teo, “Video-based point cloud generation using multiple action cameras,” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 40, p. 55–60, 2015.
- [20] C. Balletti, F. Guerra, V. Tsioukas e P. Vernier, “Calibration of action cameras for photogrammetric purposes,” *Sensors*, vol. 14, p. 17471–17490, 2014.
- [21] P. Helmholz, J. Long, T. Munsie e D. Belton, “Accuracy assessment of go pro hero 3 (black) camera in underwater environment,” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. %1 di %2XLI-B5, p. 477–483, 2016.
- [22] F. Neyer, E. Nocerino e A. Grün, “Image quality improvements in low-cost underwater photogrammetry,” *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 42, p. 135–142, 2019.
- [23] E. Nocerino, M. M. Nawaf, M. Saccone, M. B. Ellefi, J. Pasquet, J.-P. Royer e P. Drap, “Multi-camera system calibration of a low-cost remotely operated vehicle for underwater cave exploration,” *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 42, p. 329–337, 2018.
- [24] E. Nocerino, F. Neyer, A. Grün, M. Troyer, F. Menna, A. Brooks, A. Capra, C. Castagnetti e P. Rossi, “Comparison of diver-operated underwater photogrammetric systems for coral reef monitoring,” *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 42, 2019.
- [25] M. von Benzon, F. F. Sørensen, E. Uth, J. Jouffroy, J. Liniger e S. Pedersen, “An open-source benchmark simulator: Control of a bluerov2 underwater robot,” *Journal of Marine Science and Engineering*, vol. 10, p. 1898, 2022.
- [26] Z. Liu, Z. Meng, N. Gao e Z. Zhang, “Calibration of the relative orientation between multiple depth cameras based on a three-dimensional target,” *Sensors*, vol. 19, p. 3008, 2019.
- [27] A. S. Olagoke, H. Ibrahim e S. S. Teoh, “Literature survey on multi-camera system and its application,” *IEEE Access*, vol. 8, p. 172892–172922, 2020.
- [28] E. Mitishita, J. Côrtes, J. Centeno, A. M. L. Machado e M. Martins, “Study of stability analysis of the interior orientation parameters from the small-format digital camera using on-the-job calibration,” in *Canadian Geomatics Conference*, 2010.
- [29] F. Menna, E. Nocerino e F. Remondino, “Flat versus hemispherical dome ports in underwater photogrammetry,” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 42, p. 481–487, 2017.