Architecture of a Low-Cost Solution for ROVs to Improve Navigation and Data Collection

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Abstract.
The documentation, conservation, and preservation of underwater archaeological sites is conventionally performed by divers in shallow waters. However, when dealing with significant depths, the sites can be inaccessible for humans, presenting significant challenges and risks, making these activities hazardous. Recently, the use of robotic platform such as remotely operated vehicles (ROVs) allows to overcome the difficulty of such a harsh environment. Nevertheless, professional-grade ROVs employed for this purpose are expensive and specifically designed with integrated advanced sensor systems for data acquisition and navigation. In the context of the MSCA-RISE H2020 Technological Consortium TO develop sustainability of underwater Cultural heritage (TECTONIC) project, a solution consisting of a optical payload and an acoustic localization system for low-cost ROV, was defined in order to support ROV pilots during documentation and monitoring activities. The project aims to preserve underwater cultural heritage (UCH) encompassing the selection of a commercially available ROV and the definition of a customized hardware/software (HW/SW) architecture. After market research, a suitable commercial off-the-shelf (COTS) low-cost ROV was defined and used as the foundation for integration. Mechanical, electric, and data interface modules were designed to seamlessly integrate and manage the sensor suite. The results of the integration demonstrate the potential of the chosen algorithms and the sensor suite for improved navigation and data collection in challenging underwater environments, where high-grade and expensive sensors are not available, thereby making more accessible the field of underwater survey missions.

Keywords: Underwater Cultural Heritage (UCH), Underwater 3D Reconstruction, Underwater Mapping, Underwater Localization, Underwater Survey.

1 Introduction

Preserving UCH sites, such as shipwrecks, sunken cities, and prehistoric artwork and treasures, is of utmost importance [1,2]. Documentation, conservation, and preservation measures must be implemented, while also increasing public awareness and knowledge. The EU-funded TECTONIC project aims to foster interdisciplinary collaboration among academic and non-academic professionals in the UCH field. By leveraging their expertise, the project seeks to address the complex challenges [3] that still exist in this domain. The project will facilitate knowledge exchange and provide training for the utilization of advanced techniques, instruments, and methods. It aims to establish strong links between research, higher education, and business. In the TECTONIC project [4], was evaluated the feasibility of employing cost-effective robotic systems for exploring, documenting, and safeguarding UCH. The majority of robotic systems consist of ROVs equipped with sophisticated sensors, but their cost makes them inaccessible to a broader audience. At the same time, such sensors are necessary to prevent damage on the inspection site. Precise and controlled manoeuvring plays a critical role in specialized fields like cultural heritage preservation, where unintentional movements can cause damage to valuable artifacts [5]. Likewise, in photogrammetry mapping missions, a deficiency in environmental perception can result in incomplete area coverage and the production of low-fidelity 3D reconstructions. Another relevant issue is the accurate georeferencing of defined assets in such as environment. Underwater localization technologies exploit the physical properties of sound and signal processing algorithms to determine the position of a sound source concerning a set of beacons arranged in reference points [6]. By incorporating a stereo camera, employing computer vision algorithms for both localization and mapping, it becomes possible to enhance environmental perception [7,8]. This technological approach offers several benefits, particularly in terms of real-time data processing [9]. This capability allows for immediate verification of collected data, ensuring that ongoing missions adhere to the required standards. The stereo camera configuration provides on-the-fly quantitative spatial information, thereby facilitating piloting and operational tasks.

Consequently, this paper presents the architectural design of a robotic platform specifically developed to integrate optical sensors and an acoustic localization system. The main objective of this platform is to support the ROV pilot in navigation tasks and data georeferencing by utilizing a computer vision based solution to get proprioceptive parameters [10] and an acoustic localization system. The proposed solution mainly includes valuable feedback on navigation velocity, the distance between the camera reference frame and the target, and the ground sample distance.

The structure of the paper is as follows: Section 2 presents a comprehensive overview of the system architecture, outlining the components and the integration of the proposed solution into a commercially available and cost affordable small ROV. Following this, section 3 presents the results obtained from controlled environment experiments and simulations. Finally, the last section concludes the paper and discusses potential avenues for future testing and application.

2 System Architecture

The typical survey scenario is depicted in Fig. 1. The ROV moves on the seafloor while acquiring images of the relevant asset with both the cameras and being located by the means of the acoustic localization system. The cable connection between the ROV and the surface control unit facilitates offloading a portion of the computational load onto the surface control unit, which can manage camera control, acquisition parameters, and execute computer vision/artificial intelligence algorithms for mapping and, eventually, target classification in the underwater environment.

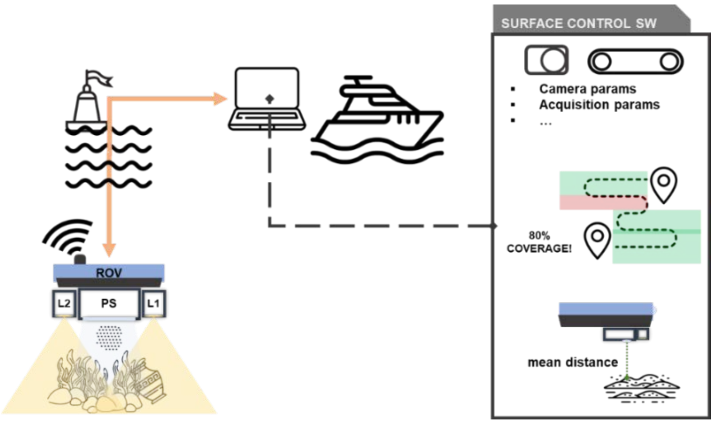


Fig. 1. Schematic diagram of the survey scenario.

An extensive market survey was conducted to identify and select the appropriate COTS platform. The choice was to develop the proposed solution in the environment of the BlueROV2 Rev3 [11] due to its affordability for small research groups and small size. Various architectural options were assessed based on factors such as cost, requirements, and application scenarios. The specification and the goal of the TECTONIC project leaded to the architecture of Fig. 2. The system consists of a mono-camera, a stereo-camera, a lighting system, a battery pack and an acoustic localization system.

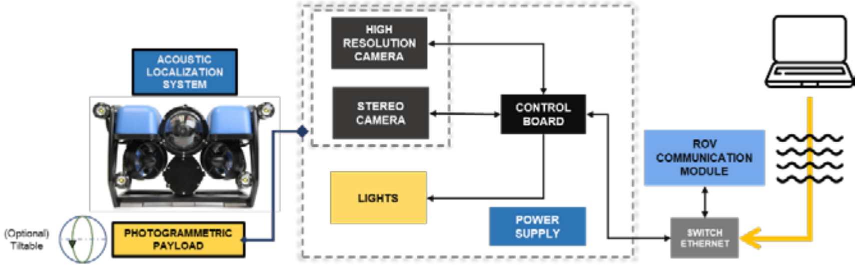


Fig. 2. Architecture of the sensor with connections. The photogrammetric payload is attached to the bottom of the ROV and an optional tiltable system can allows to set the proper acquisition angle.

Considering the above-described scenario, the mono-camera is employed for offline high-resolution 3D reconstruction, whereas the stereo-camera is responsible for real-time extraction of spatial information from the scene. An internal power supply is necessary since the ROV's tether does not provide power. The acoustic localization system allows georeferenced data and to supply additional data for navigation.

With the aim of remote controlling the camera, the GoPro Hero 9 Black [12] was chosen. This camera offers a wide field of view (FOV) and a resolution suitable for high-resolution 3D reconstruction. The GoPro API allows for sending setting commands through an easily implementable communication protocol.

A thorough evaluation of commercial stereo-cameras was conducted to identify the most suitable option for the project's objectives. The ZED2i [13] camera offers a wide field of view (FOV) and a robust design that aligns well with the compact dimensions of the ROV. Additionally, it is equipped with an integrated IMU, and a dedicated processing unit tailored for artificial intelligence applications. Although the camera's low frame rate may be perceived as a limitation in some scenarios, it does not pose a drawback in our specific application. Moreover, it allows to resize the images to increase the frame rate if necessary.

Both the cameras are synchronized and managed by a custom software installed on the surface control unit.

Given the need to have an accurate position of the underwater vehicle, essential for operating in complex underwater environments, long-baseline (LBL) systems are the most suitable solution, demonstrating a theoretical greater accuracy compared to setups with a lower baseline (short- or ultra-short- baseline) [14,15]. Fig. 3 illustrates the architectural framework delineating the constituent elements of the system and the communication logic.

To address the challenges related to rapid deployment and recovery, as well as to avoid mooring on UCH sites, the proposed architecture incorporates a network of buoys equipped with GPS and beacons. This design allows for georeferencing the buoys solely based on GPS, eliminating the need for fixed point positioning.

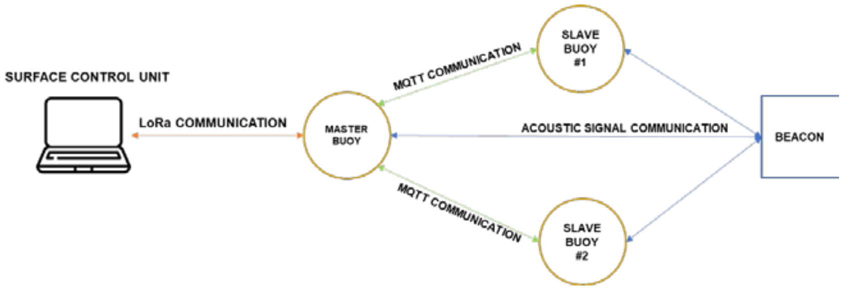


Fig. 3. LBL system architecture and communication connections.

The acoustic localization system comprises a group of three buoys (a master and two slaves), and an underwater acoustic beacon. On the surface, the communication between the master buoy and the surface control unit is through LoRa [16] technology. That technology is capable to cover a long range with relatively low energy consumption and being cost-effective in terms of hardware and maintenance. The slave buoys communicate with the master using a MQTT protocol [17], in a shorter range. In underwater, through the acoustic channel, each buoy knows the range from the beacon. The master buoy interrogates the slave buoys at different time and knowing the position of the buoys themselves and the acoustic range of each one is capable to calculate the position of the underwater beacon by trilateration.

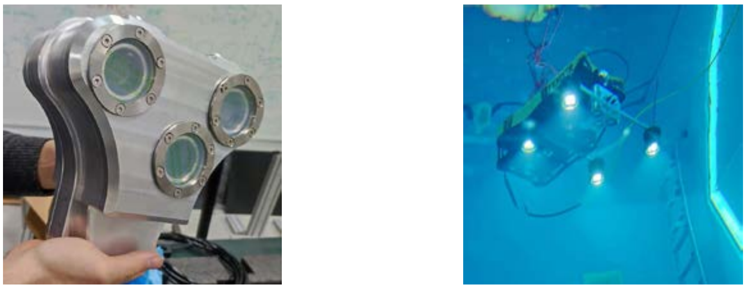
The control software is integrated in the same console that manage the optical payload. Considering the general architecture, the system allows the user different options regards the data georeferencing:

- The images are collected by the photogrammetric system and georeferenced for the sake of the acoustic localization system.
- The images are collected and georeferenced by the fusion of both acoustic localization data, additional sensors and visual odometry.
- The images are collected and georeferenced by the deployment of a SLAM algorithm which provide a scaled and globally consistent reconstruction of the seafloor.

The open-source architecture of the low-cost ROV allows strong customizations of the environment. The software is developed in the framework of the ROV and integrates the mission planner, the sensors manager module, and the elaboration module.

3 Experimentation

The system is currently undergoing development, but preliminary experimentations and simulations were already conducted. Tests and simulations involve separately the optical payload and the acoustic localization system. The optical payload was tested using a functional prototype to assess the feasibility of using computer vision to get proprioceptive parameters to aid the ROV pilot during navigation (Fig. 4). Meanwhile, the trilateration algorithms of the acoustic localization system were tested in the MATLAB [18] environment, varying the system's characteristic parameters.



(a) **(b)**

Fig. 4. Functional prototype of the optical payload (a), installed on the bottom of a professional-grade ROV (b).

The aim of the test for the optical payload is to compare the navigation solution obtained from the computer vision algorithm of the optical payload, with the fusion of professional-grade sensors, such as the Nortek DVL [19] and an accurate IMU. In particular, the comparison concerns proprioceptive parameters such as position, velocity, and additionally the distance from the target. The experimentation was carried out in controlled environment at the University of Calabria. To replicate artificial seafloor features detectable by the computer vision algorithms, a high-resolution printed canvas was placed at the bottom of a pool of dimensions 6 × 4 × 4 meters. While various SLAM algorithms can be utilized, the images were used to fed the ZED SLAM developed by Stereolabs in order to compute proprioceptive parameters of the ROV.

Prior to the experimentation, the proposed sensor was calibrated, acquiring images at different distance and angles, in the same underwater environment using a 22 × 22 checkerboard with each square side measuring 45 mm. The camera model parameters were computed scaling the 3D reconstructed scene with reference object and optimizing the calibration process in Agisoft Metashape [20]. Following the calibration dataset, two separate datasets were obtained by navigating the ROV along two trajectories and varying the height offsets by increments of 1 meter, up to a maximum of 3 meters above the pool bottom. The first dataset was acquired systematically as the ROV circumnavigated the pool perimeter, while the second dataset simulated the acquisition of transects comprising three parallel lines.

The results of the first test are shown in Fig. 5. Considering a NED reference frame, the figure depicts on the plane N-E the trajectories of the ROV navigating around the perimeter of the pool at a 1 m height from the bottom, computed by both the fusion of professional-grade sensors installed on the ROV and the ZED SLAM. On the right of the figure, the velocity computed by the sensor fusion, the SLAM, and the DVL are compared. The Root Mean Square Error (RMSE) between the SLAM and DVL velocity data is 0.095 m/s. A comparison between the distance from the bottom of the pool (in means of altitude) computed by the SLAM algorithm and the ones of the DVL sensor, along the followed path, is presented in Fig. 6. The different estimates between altitudes decreases after the closure of the loop of the SLAM algorithm.

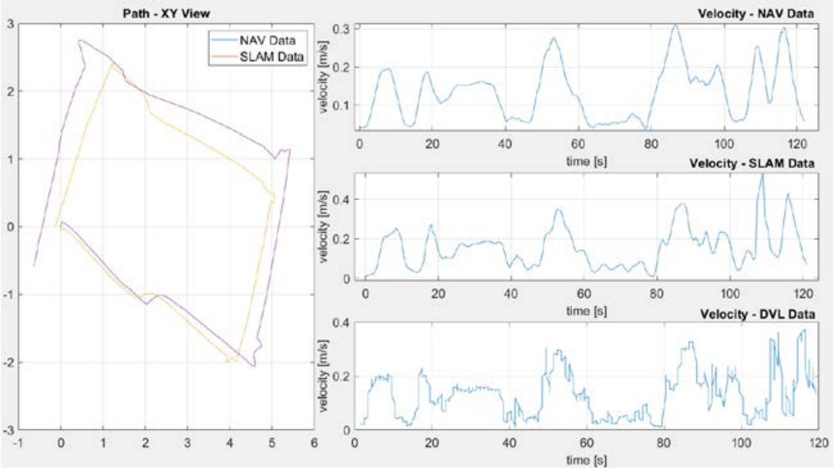


Fig. 5. Comparison between professional-grade sensor (blue path) and ZED SLAM (yellow path) navigation solution, along with velocity plots on the right.

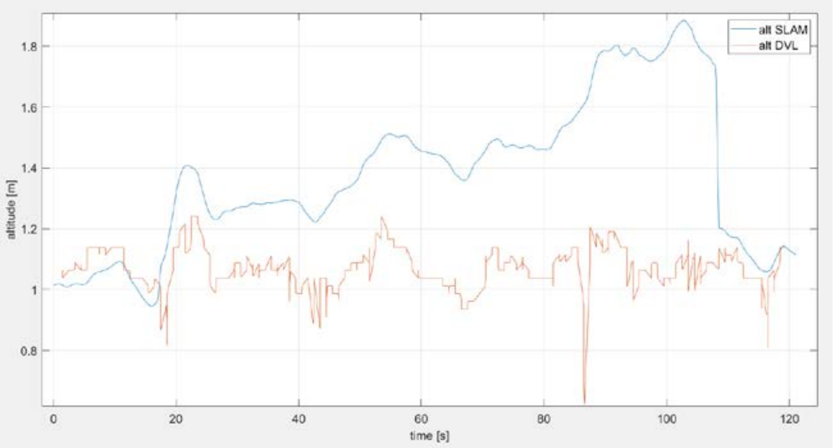


Fig. 6. Altitudes computed by SLAM (blue) and acquired by DVL (red). The error decreases when the SLAM algorithm is able to close the loop.

The statistics in Table 1 were computed by considering the fitting plane of the points in the 3D reconstruction provided by the stereo-camera, which approximates the entire 3D reconstructed surface for each pair of stereo images.

Table 1. Descriptive statistics of the ZED2i camera's distance estimation in relation to the 3D point cloud, such as mean distance, standard deviation, and percentage error.

Nominal distance [m]	Mean distance [m]	STD deviation [m]	% Error [-]
1	0.988	0.028	1.2
2	1.968	0.053	1.6

The results indicate that the errors in mean distance and velocity computed by the SLAM algorithm at each epoch do not significantly affect the performance of a photogrammetric mission. In fact, considering the characteristics of the mono-camera sensor, the RMSE in velocity only causes a variation in the overlap of approximately 2% at a frame rate of 15 frames per second and an altitude of 1 m when advancing in the direction of the sensor's height.

Regards the acoustic localization system, the goal of the simulations is to assess the performance of state-of-the-art trilateration algorithms in order to define the one that guarantees the minimum error for a given setup. In addition to the classic spherical trilateration algorithm, two iterative algorithms were evaluated in terms of performances: Gauss-Newton and Levenberg-Marquardt. Following the guidelines and assumptions of the simulation methodology proposed in literature [21], the schematic model of the process, depicted in Fig. 7, was defined. Assuming the error of each sensor involved in the LBL system [21,22], the ranges and the GPS position of the buoys were computed as input for the simulation. Then, the positioning of the acoustic unit is estimated and compared with the reference position using the different algorithms.

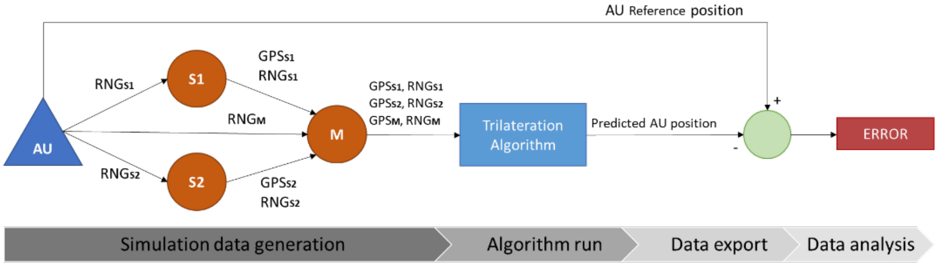
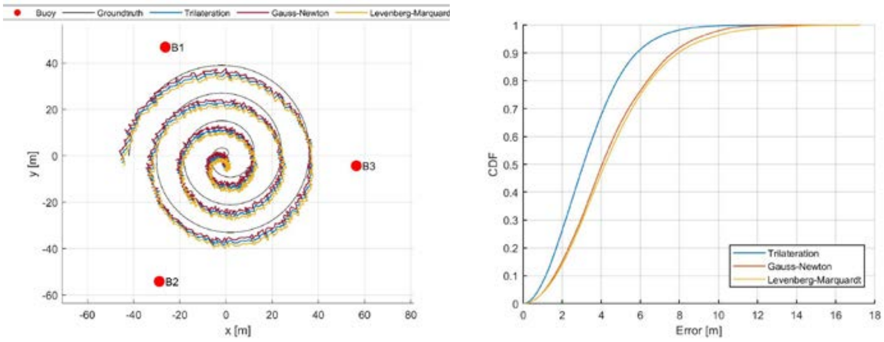


Fig. 7. Schematic model of the simulation process. AU – underwater beacon; M – Master buoy; S – Slave buoys.

It has been assumed that the acoustic unit moves according to a spiral trajectory at a given depth which remains within the perimeter identified by the three buoys. For the simulation it is considered a baseline of 100 m, a mean error on ranging of 1 ± 0.5 and a circular error probable on GSP of 3 m.

Fig. 8a illustrates a sample of the reference spiral trajectory of the vehicle and the estimated trajectory. It can be observed that the estimated positions obtained from Gauss-Newton and Levenberg-Marquardt algorithms are very similar. After 400 simulation runs, the cumulative distribution function (CDF) of the absolute error was evaluated, Fig. 8b. The behavior of the functions confirms that the spherical trilateration algorithms outperform Levenberg-Marquardt and Gauss-Newton algorithms for the given system configuration. Specifically, for the simulation runs, the 95% error is estimated to be 9.31 m for Levenberg-Marquardt, 6.88 m for spherical trilateration, and 9.00 m for Gauss-Newton.



(a) **(b)**

Fig. 8. Results of the simulation carried out in MATLAB for the given system configuration.

4 Conclusions

The paper presents the architecture of a low-cost robotic platform system, proposed in the MSCA-RISE H2020 TECTONIC, for the documentation and mapping of UCH sites. In particular, the solution here presented aim to support ROV pilots in underwater documentation activities such as mapping and georeferencing of collected data. The solution takes advantage of a stereo-camera system to compute an online 3D reconstruction of the environment using a computer vision algorithms and an acoustic localization system in LBL configuration to known the vehicle and hence the acquired data. Furthermore, the data of the underwater scene, acquired by the stereo-camera allows to compute useful parameters used to increase the perception of the pilot while the mission is ongoing, when expensive sensors are not available. These parameters includes position, navigation velocity, distance between the camera reference frame and the target.

The results of the experimentation with a functional prototype can be considered satisfactory; comparing the SLAM results with the navigation solution provided by the sensor fusion, the RMSE on the velocity can cause a variation in the overlapping of two consecutive images of about 2% on a range of 70-80%. Regarding the acoustic localization system, the results concerning the performance of the three tested trilateration algorithms indicate that the spherical trilateration algorithm performs better than the iterative methods. However, further investigation is deemed necessary to assess the influence of the system's characteristic parameters and improve its performance. This could involve conducting a Design of Experiments (DOE) analysis to explore potential enhancements or further experimental tests on the field. Although development is ongoing and further testing is needed, the results are promising and demonstrate that the proposed solution can be used complementarily to expensive sensors with an acceptable degree of accuracy.

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References

1. Ricca, M., & La Russa, M. F. (2020). Challenges for the protection of underwater cultural heritage (UCH), from waterlogged and weathered stone materials to conservation strategies: An overview. Heritage, 3(2), 402-411.
2. Ricca, M., Alexandrakis, G., Bonazza, A., Bruno, F., Davidde Petriaggi, B., Elkin, D., ... & Francesco La Russa, M. (2020). A sustainable approach for the management and valorization of underwater cultural heritage: new perspectives from the TECTONIC project. Sustainability, 12(12), 5000.
3. Gambin, T., Bravo-Morata Rodríguez, A., & Sausmekat, M. (2021). From Discovery to Public Consumption: The Process of Mapping and Evaluating Underwater Cultural Heritage in Malta. Heritage, 4(4), 2732-2745.
4. TECTONIC Project Website. Available online: https://www.tectonicproject.eu/, last accessed 2023/05/01.
5. Bruno, F., Lagudi, A., Barbieri, L., Rizzo, D., Muzzupappa, M., & De Napoli, L. (2018). Augmented reality visualization of scene depth for aiding ROV pilots in underwater manipulation. Ocean Engineering, 168, 140-154.
6. Su, X., Ullah, I., Liu, X., & Choi, D. (2020). A review of underwater localization techniques, algorithms, and challenges. Journal of Sensors, 2020.
7. Rossi, M., & Dooly, G. (2018). Real-time vision systems for underwater robotics.

8. Laranjeira, M., Arnaubec, A., Brignone, L., Dune, C., & Opderbecke, J. (2020). 3D perception and augmented reality developments in underwater robotics for ocean sciences. *Current Robotics Reports*, *1*, 123-130
9. Tippetts, B., Lee, D. J., Lillywhite, K., & Archibald, J. (2016). Review of stereo vision algorithms and their suitability for resource-limited systems. *Journal of Real-Time Image Processing*, *11*, 5-25.
10. Conte, G., Zanoli, S. M., & Scaradozzi, D. Guide and Control of an Unmanned Underwater Vehicle by Visual-feedback Techniques.
11. BlueROV2 product website. Available online: https://bluerobotics.com/store/rov/bluerov2/, last accessed 2023/05/01.
12. GoPro Hero 9 Black product page, https://gopro.com/it/it/shop/cameras/hero9-black/CHDHX-901-master.html, last accessed 2023/05/01.
13. Zed2i product page, https://www.stereolabs.com/zed-2i/, last accessed 2023/05/01.
14. Cario, G., Casavola, A., Gagliardi, G., Lupia, M., & Severino, U. (2021). Accurate localization in acoustic underwater localization systems. *Sensors*, *21*(3), 762.
15. Bruno, F., Lagudi, A., Ritacco, G., Agrafiotis, P., Skarlatos, D., Čejka, J., ... & Simon, B. (2017). Development and integration of digital technologies addressed to raise awareness and access to European underwater cultural heritage. An overview of the H2020 i-MARECULTURE project. *OCEANS 2017-Aberdeen*, 1-10.
16. LoRa website. Available online: https://lora-alliance.org/about-lorawan/, last accessed 2023/05/01.
17. MQTT website. Available online: https://mqtt.org/, last accessed 2023/05/01.
18. MATLAB website. Available online: https://it.mathworks.com/products/matlab.html, last accessed 2023/05/01.
19. Nortek DVL 1000 product website. Available online: https://www.nortekgroup.com/products/dvl-1000-300m, last accessed 2023/05/01.
20. Agisoft website. Available online: https://www.agisoft.com/, last accessed 2023/05/01.
21. Aparicio, J., Jiménez, A., Álvarez, F. J., Ruiz, D., De Marziani, C., & Ureña, J. (2016). Characterization of an underwater positioning system based on GPS surface nodes and encoded acoustic signals. IEEE transactions on instrumentation and measurement, 65(8), 1773-1784.
22. Turetta, A., Casalino, G., Simetti, E., Sperindè, A., & Torelli, S. (2014, September). Analysis of the accuracy of a LBL-based underwater localization procedure. In 2014 Oceans-St. John's (pp. 1-7). IEEE.