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MANATEE Project: Monitoring and Mapping of Marine Habitat with Integrated Geomatics Technologies

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***Abstract*—Italian seas are home to a unique heritage of biodiversity in terms of species and habitats and are protected by EU conventions and directives. To preserve this richness effectively, monitoring activities are key to assess its state of health and evolution, and to enhance our current knowledge of natural processes and stress factors. Where this heritage is compromised, restoration projects can be undertaken, operations requiring the application of technical and scientific methods to ensure robust, reliable and cost-effective data collection. The ensemble of Geomatics techniques can provide valuable support for marine habitat monitoring, in the form of: localization, navigation and mapping of the site of interest following autonomous or guided approaches; generation of digital twins (3D models) of the habitat at the required resolution and accuracy; extraction from the digital twins of statistically significant metrics to assess the time evolution; presentation and sharing of the results with both the scientific community and the general public to promote awareness of environmental protection issues. MANATEE (Monitoring and mApping of mariNe hAbitat with inTegrated gEomatics technologiEs) project is providing these monitoring solutions via the integration of underwater photogrammetry with auxiliary positioning and navigation techniques based on acoustic, pressure and inertial sensors. The developed approaches is implemented in three complementary underwater vehicles, differing in cost, weight and portability, number and grade of navigation, positioning and 3D modelling sensors, and designed to cover habitats different for extension and depth. An observation class UUV (Unmanned Underwater Vehicle), a low-cost micro ROV (Remotely Operated Vehicle), and a 3D surveying and modelling device for scuba divers will be tested in a real-world experiment focusing on the restoration of a crustose coralline algae, Lithophyllum stictiforme.**

***Index Terms*—monitoring, inertial navigation, restoration of marine habitat, underwater photogrammetry**

I. Introduction

Marine habitat and species monitoring is enforced in Marine Protected areas (MPAs) and Natura2000 sites and Geomatics techniques are partially exploited for them. Side scan sonar and multibeam echosounder are indicated to assess the habitat extension, while its status is monitored using images and videos acquired with ROVs (Remotely Operated Vehicles) or SCUBA divers. Positioning techniques, such as GPS, are recommended for determining the position of areas to be monitored (at the sea surface) and are generally integrated with satellite or aerial drone imagery for shallow water surveys (e.g., observation of marine species and habitat monitoring). Thanks to the availability of affordable photographic systems and easy-to-use processing tools, marine ecologists are increasingly employing photogrammetry for habitat monitoring, such as coral reefs [1], [2] or seagrass meadows [3]. This task is generally carried out by divers following procedures designed to maximise photographic coverage while respecting the time constraints under water [3], [4]. Unfortunately, these are not often designed considering photogrammetric criteria, i.e. do not assure a redundant and robust network for self-calibration: e.g., swimming paths do not include oblique views, crucial to mitigate photogrammetric model deformations [1], [5] and time and economic constraints limit the use of reference points of known coordinates to check and limit possible deformations. Scale ambiguity is generally solved using known length scale bars, but in materialising a stable network of reference points the tendency is to limit the number of measured points to two, in the case of transects and four for square or rectangular plots, thus decreasing redundancy. Verifying in real-time the quality of imaging configuration is particularly challenging under water, regardless of the chosen survey method (diver or remotely controlled device): although some supporting solutions have been proposed [6], none of them became a standard. The use of unmanned vehicles allows to extend the depth and time limits affecting the divers' survey. In the last decades, scientific and technological developments led to the use of underwater robotics in many application and research domains [7], including exploration and monitoring of underwater environments [8]. Marine robots include unmanned surface vehicles (USVs) and Unmanned Underwater Vehicles (UUVs). Two UUV subcategories can be identified: Autonomous Underwater Vehicles (AUVs) are able to conduct their mission without operator intervention, going back to a pre-programmed location and allowing data download at the end of the survey. ROVs are instead connected to a ship by cable, which transmit commands from the Remote Station to control the vehicle and allow for the data acquisition in real time. UUVs present more challenges than surface or aerial vehicles, e.g. the absence of reception of the GNSS (Global Navigation Satellite Systems) signals as soon as the vehicle dives. For this reason, once the GNSS geographic position is acquired at the sea surface, UUVs navigation is performed through inertial and acoustic integrated techniques. To further improve autonomous navigation and mapping capabilities, other technologies can be integrated, mainly based on optical sensors and computer vision algorithms (e.g., SLAM - simultaneous localization and mapping) [8]. Moreover, the limited bandwidth available for data transmission via acoustic modem between the submarine vehicle and the support vessel need to be handled if no umbilical cable is provided. Furthermore, multi-sensor fusion methods for UUV positioning are affected by divergence, noise, multi-path and outliers that have a significant impact on positional accuracy [9]. Obstacles to the widespread use of UUVs include their high cost and difficulties in logistics and use. In response to this, several low-cost solutions have been proposed in recent years. Probably the most well-known to the international scientific community is the BlueROV2, a low-cost micro ROV provided with an open-source software. Easy to control and with a nominal maximum operational depth of 100m, it can be configured with different equipment to suit the needs of the mission/research [10]–[12].

II. Methods

A. Context and motivations

The protection of our seas is so vital that the United Nations has proclaimed the years 2021-2030 "Decade of Ocean Science for Sustainable Development". The goal is "to support efforts to reverse the cycle of decline in ocean health" and ensure that "ocean science can fully support countries in creating improved conditions for sustainable development of the Ocean" [13]. The decline of marine ecosystems and current lack of effective solutions for reversing this trend have triggered growing interest in developing tools for the restoration of degraded marine environments [14]. Monitoring is a crucial activity to establish the health of the environment, its evolution and to deepen our understanding of the delicate phenomena and equilibria underlying it. Similarly, Marine Ecosystem Restoration (MER) projects require monitoring tools to assess their effectiveness. The basic approaches are outlined in European directives that have been transposed at national level, while it is the task of research to identify and propose new methods to make monitoring increasingly effective, objective and efficient. The lack of up-to-date information on the environmental status of underwater habitats is a major problem, especially in areas that are deeper and cannot be reached by divers. Due to this lack of data it is not possible to ensure effective management of these sites and to guarantee a good conservation status of the habitats. There is a wide variety of marine habitats. In this project we will focus on coralligenous reefs, unique biodiverse ecosystems fulfilling fundamental functions of carbon sinks [15], and provision of habitats for economically valuable species [16], [17]. The foundation of these habitats are Coralline Algae (CA), which include Crustose Coralline Algae (CCA), but are currently experiencing a loss of vitality [18], and are considered highly vulnerable to long-term climate change [17], [19]. One of the main bio-constructor of the coralligenous reefs in the Mediterranean Sea is the Lithophyllum stictiforme, a CCA generally growing from 20 metres deep up to over 100 metres, but occasionally observed also near the surface. MANATEE (Monitoring and mApping of mariNe hAbitat with inTegrated gEomatics technologiEs) wants to contribute to the challenge of environmental monitoring. To this end, MANATEE will prove a synergistic use of geomatic techniques implemented on different systems to respond to monitoring needs at different resolutions, and depths through non-invasive, non-destructive 3D surveying and modelling approaches (Fig. 1).

B. Objectives

The goals of the MANATEE project can be outlined as follows:

- define a multi-resolution positioning, navigation and mapping integrated approach: from coarse/low resolution with multibeam coupled with acoustic positioning, to fine/high resolution with optical sensor
- demonstrate the effectiveness of the multi-resolution approach on different vectors, which can cover different depths and areas
- develop a framework for: acquisition planning ensuring that the monitoring requirements are met and assist and guide the survey with real-time evaluation of the results
- mitigate the need of a materialised network of reference points on-site via artificial intelligence approaches- AI
- showcase the developed methodologies in real-case monitoring activities in MER projects
- potentiate an effective collaboration between Geomatics, marine ecology researchers and Marine Protected Areas (MPAs)

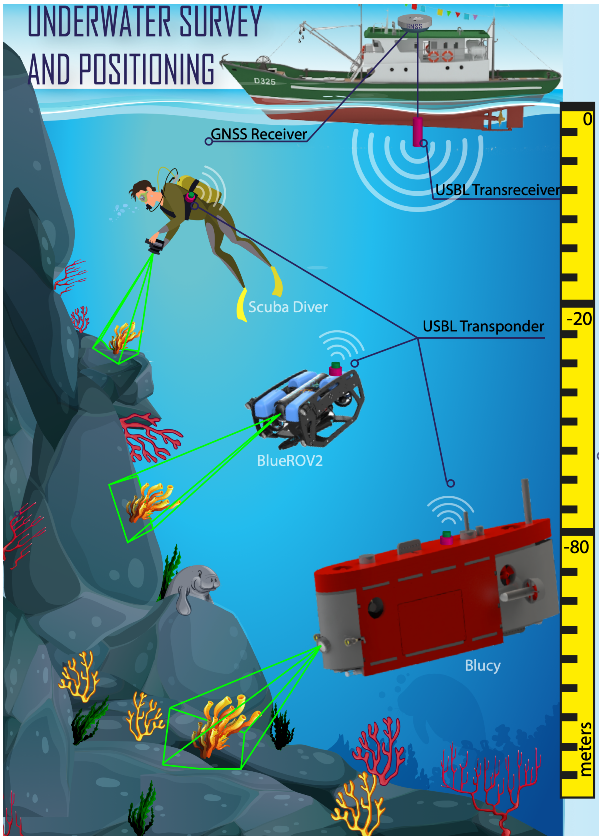

Fig. 1. Synergistic use of geomatic techniques implemented on different systems in MANATEE project.

- outline a set of guidelines enabling the effective monitoring of coralligenous ecosystems through UUVs and divers-performed surveys and 3D data analysis
- enhance public awareness on the topic of protection, preservation and restoration of the marine environment

C. Activities

The proposed methodology is based on the integration of geomatic measurement techniques defining a common framework for divers and ROVs. Specifically, the GNSS positioning system allows to define, with submetric accuracy, the starting point on sea surface of the vehicle or the diver, once submerged they are able to reach the monitoring target area using an innovative navigation system based on the integration of Inertial Sensors, USBL and Visual-SLAM. The project will be implemented according to the following activites.

D. Shallow depth Visual-Inertial-Pressure mapping device: VIP for divers

This activity focuses on the development of a device designed to guide a diver to survey the area of interest. Compared to the other two systems presented in following activites, its range of application is adapted to the depths and operating times of a diver (max 60 m and 1h survey). VIP for divers is based on the system presented in [20]: an ARM-based, low-cost stereo camera equipped with pressure and inertial sensors in a waterproof housing. The 'brain' of VIP for divers is an algorithmic framework based on visual-inertial-pressure SLAM that guides the diver through the survey. The user defines the requirements for the mapping in terms of resolution and accuracy (Fig. 2); VIP guides the user by showing the progress of the acquisition in real time, also providing quality features (GSD, redundancy, estimated precision) of the achieved result. If the area of interest is known, e.g. from a previous survey, VIP for divers designs the camera network and during the acquisition checks that it is respected with in-line (real-time) feedback. A multi-resolution approach might also be implemented: if a coarse 3D model is available, from e.g. a multibeam survey, VIP for divers will program and guide a second acquisition at the desired higher resolution. The integration of pressure and inertial sensors will define four of the seven parameters needed to define the 'datum' or reference system, i.e. the scaling [21] and orientation of the photogrammetric model. VIP will be also equipped with a GNSS receiver to locate at the sea surface the diving area in a geographic reference system. As part of this activity there is also the development of Artificial Intelligence (AI) approaches for the recognition and segmentation of stable features in the habitat in the case of a solid substrate [22]. These elements will be used to align successive epochs. In cases of changing or dynamic substrate (sand, mud, posidonia meadows), more traditional positioning approaches based on the integration of GNSS at the water surface and in-water acoustic techniques will be tested by equipping the diver with an acoustic transponder. While in real-time VIP for divers will show a rough 3D model for guidance purposes, in post-processing (off-line) a full resolution digital twin will be generated via dense photogrammetric algorithms. VIP for divers along with the two other platforms will be showcased in the real-life experiments described in II-G. To realise VIP for divers, the activity will be structured in four tasks:

- hardware development
- VIP SLAM for real time navigation, re-positioning, mapping and quality check
- real time segmentation via AI approaches
- off-line dense digital twin (3D model) of the mapped habitat with segmentation of features of interest.

E. Medium depth low-cost micro remotely operating mapping system: BlueROV2

The activity focuses on the development of high-precision survey techniques at medium depths using a low-cost Micro-ROV (such as BlueROV2, Fig. 3). This type of ROV can reach depths up to 100 m, although for this project the operational depths shall be between 5 and 50 metres. A MicroROV is easy to transport since its dimensions and weight allow it to be loaded on board small vessels and inflatable boats; moreover its configuration is completely customizable. The main goals of this activity are to develop a methodology for obtaining a high accuracy metric multi-resolution 3D model of a target submarine area, and to define an Integrated Navigation System for guiding the ROV during the survey operations. The

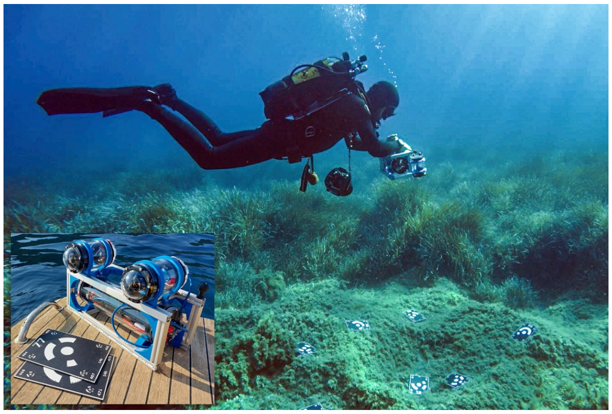

Fig. 2. Frog [20], the system on which VIP will be further developed, in action.

BlueROV2 in developer version, can be equipped with several sensors for navigation and survey purposes; furthermore, an SDK allows it to program a custom autopilot. Finally, the acoustic images provided by the acoustic camera can be used for obtaining a different texturing layer of the 3D model. This activity is divided in the following tasks:

- Hardware Equipment
- Navigation System Development and Calibration
- Multi-resolution survey systems development and calibration
- Testing in Laboratory and Pool.

The output of this activity will be adopted for performing the activities described in II-G.

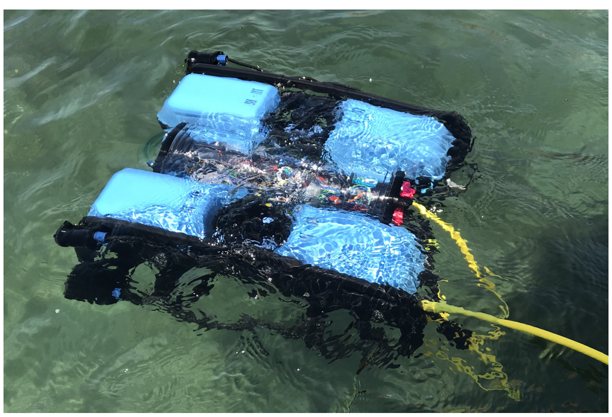

Fig. 3. MicroROV BlueROV2 engaged in surveying activities.

F. High depth observation class UUV: Blucy

This activity focuses on the deployment of an UUV capable of diving in areas deeper than 60 m, depth beyond which operational and safety limits arise for normal activities with divers. Within the INTERREG Italy-Croatia SUSHI-DROP project (SUstainable fiSHeries wIth DROnes data Processing) a prototype UUV, named Blucy (Fig. 4), with unique features for marine monitoring has been designed and implemented [23]. Blucy is a hybrid UUV that can be used as ROV for missions in complex environments or as an AUV for automatic instrumental surveys of larger areas. The characteristics of the UUV allow diving to depths of up to 250 metres, even in ROV mode, thanks to a lightweight reinforced bidirectional communication fibre optic cable more than 500 metres long that guarantees the connection with the surface vessel to control the UUV and receive the data in real time. Blucy is a versatile open system that offers the possibility of different configurations for scientific payloads. In fact, it is possible to replace or reconfigure the various scientific subsystems, adapting them to the specific operational scenario of the mission. Thanks to these characteristics, Blucy represents within the project the reference tool to test the accuracy of positioning techniques based on the different approaches. The activity will be structured in three tasks:

- Subsystems calibration in surveyed environment
- Support for precision navigation, to allow refined positioning close to survey elements and to optimally align surveys carried out in consecutive time intervals
- Multi-resolution approach from coarse to high geometric resolution volumetric evaluation of growth of identified species.

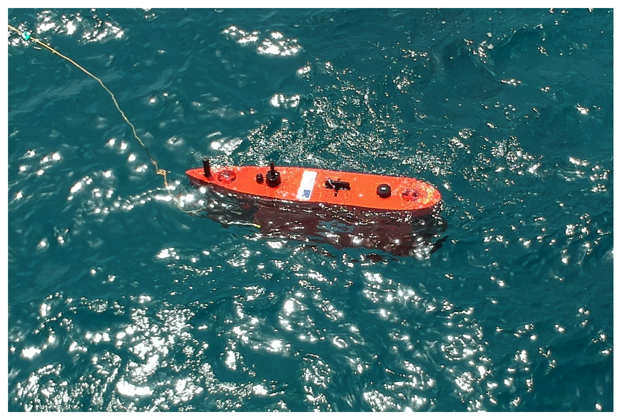

Fig. 4. Blucy, prototype UUV designed and implemented in SUSHI-DROP project [23].

G. Comparing and stressing the three platforms: real-world experiments

The main goal is to test the effectiveness of the developed techniques in a real marine scenario, in order to validate, compare and further refine the proposed approaches and finally provide a fully-integrated system for multi-resolution underwater surveys. To this aim, the collaboration between the MANATEE team, marine ecology researchers and Marine Protected Areas (MPAs) officers is required. Three test sites have been identified: Costa Paradiso in Sardinia and the two MPAs of Punta Campanella and Gaiola both in Campania. All the locations are within the Natura 2000 network. Costa Paradiso is the setting of a MER project established by Prof. Giulia Ceccherelli (University of Sassari), focusing on Lithophyllum stictiforme, a crustose coralline alga (CCA) and a main bio-constructor of the coralligenous reefs in the

Mediterranean, which is also present on the other two sites. Prof. Ceccherelli's project involves first growing the algae samples on blocks which are then transplanted to another location that needs to be restored. Before being transplanted, the samples undergo a colouring process; to assess their growth, the samples are removed, sliced and the growth estimated through the distance between the outer and coloured layers. The three MANATEE systems (VIP for divers, BlueROV2 and Blucy) will be all deployed in one of the sites restored as part of Prof. Ceccherelli's project at a depth range between 20m and 35m. A first survey will be planned in the second half of the first year of MANATEE; a second survey will be realised after about 10 months. This time interval, necessary to observe the growth of the algae samples, will also be used to improve the platforms in the light of the first results. In these tests all the systems will be used at the same depth and on the same samples using the higher performance system (Blucy) as a benchmark for the other two (VIP for divers, BlueROV2). The two successive epochs will be co-registered following a two-step approach: a 'coarse' positioning in a global reference system using the GNSS and acoustic systems and a fine sub-centimetre registration exploiting stable substrate features detected through AI algorithms and VIP-SLAM (II-D). The results will be compared against those obtained with traditional techniques, i.e. sampling collection and laboratory analysis. Metrics of interest (growth, thickening, etc.) will be extracted in cooperation with marine ecologists and biologists who have expressed their interest in the project (section 3.2). Maps of change detection with significance analysis [1] will be also proposed as a tool to assess the growth of the samples. The tested methodologies will be then used in the two MPAs, where the surveys could be carried out with the three vehicles used at different depths.

III. Results and discussion

Although still in progress at the time of writing this extended abstract, MANATEE project expected results can be summarised as follows:

- Implementation of a 3D underwater positioning/localization approach with an accuracy potential suitable for measuring the evolution of the same biological colony, through non-destructive surveys carried out over time. Two-step strategy is: (i) the absolute referencing (in e.g. WGS84) via GNSS plus USBL system is refined with a (ii) precise sub-centimeter relative positioning using VIP-SLAM and AI, exploiting stable elements of the seabed. For those areas where it is not possible to detect stable elements, the potential of absolute positioning with low-cost and high-cost sensors will be assessed.
- Improvement of environmental monitoring techniques, also for the specific needs of MER, thanks to the synergic use of accurate positioning, 3D mapping and modelling and AI. Compared to the traditional approaches recommended by the current directives that rely on the expertise of the single operator, the methods proposed within MANATEE are designed to assist survey and measurement operations, ensuring effective monitoring. The use of 3D approaches will also enable a comprehensive assessment of habitat evolution, while still allowing for the extraction of more traditional metrics.
- Drafting of guidelines for an effective monitoring with different 3D surveying and modelling systems, from divers to UUVs. To make the MANATEE procedures exploitable by the scientific community and MAPs officers in their daily practice. Protocols will be derived from the experiences gained in the experimentation for both the use of different surveying configurations (divers and UUVs) and analysis of the monitoring products (multi-epoch digital twins/3D models).
- Raising scientific and public awareness on protection and restoration of marine habitat via the exploitation of 3D mapping and immersive visualisation techniques. To foster the spread of MANATEE results, gathered data and developed open source algorithms will be respectively in online repositories under open data licence for the benefit of scientific peers.

A. *Scientific and technological impact*

The application potential of MANATEE is mainly related to the provision of non-invasive monitoring methodologies for the marine environment, particularly required in operations such as the restoration of coralligenous species in marine protected areas, as well as in places where monitoring the impact of engineering infrastructure on the marine environment is of great importance. In this regard, the project aims to develop guidelines to increase the effectiveness of current monitoring procedures, both with divers equipped with a camera and UUV systems. The project results are applicable to submarine environments present at various depths, which implies that the application potential is wide. The main results of the research project are expected with an interdisciplinary approach, based on the knowledge of all research units in the field of Geomatics and with significant contributions from experts and scholars in marine ecology and biology and with the support of the managers of the marine protected areas where the experiments will be performed. The produced digital twins and its virtual exploration can be further exploited also for training in marine environment monitoring operations, allowing to learn how to optimise, from a photogrammetric point of view, the phase of image acquisition.

From a scientific point of view, the large amount of data that can be recorded during each underwater survey will support the realisation of interdisciplinary studies, comparing or correlating the measurements obtained with different on-board sensors, involving marine sciences and different engineering fields. The new device for divers (VIP for divers) will extend the frontiers of surveying, making every diver a surveying 'expert'. Designed in a modular and 'open' way, it could form the basis for the development of other platforms. The optimization of the BlueROV2 navigation and positioning techniques through the integration of low-cost sensor systems will give an important contribution to the scientific community involved in survey and monitoring operations, especially in view of the recent efforts in providing low-impact and accessible-to-all technologies which are still able to ensure robust, reliable and accurate results. Moreover, the enhancement of the VIP-SLAM algorithms and of the mapping procedures through the combined use of different sensors will greatly support the underwater research at a multi-resolution level. From a technological point of view, by continuing the development and missions carried out with the Blucy UUV prototype, it is possible to further optimise its characteristics and operational capabilities with the future aim of creating a fleet of low-cost but high-tech UUVs.

IV. Conclusions and Future Developments

MANATEE project shows monitoring possibilities with the integration of surveying and positioning techniques, implementing them in three complementary underwater vehicles. The ability to measure the growth of the algae by a few mm/year will showcase the benefits and adaptability of the developed Geomatic approaches in real monitoring projects, demonstrating their measurement potential in a contactless and non-impacting way on the environment without requiring samples to be collected. The results achieved will have a broader impact, extending beyond the boundaries of environmental monitoring to other sectors such as industrial facilities monitoring or archaeological applications. The increasingly effective use of UUVs and AUVs surveying techniques also has significant impacts in contexts beyond environmental monitoring. The further developments and skills acquired during this project can be replicated in the industrial underwater sector, such as the survey and planned maintenance of submarine engineering structures and infrastructures.

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