Acoustic seafloor mapping using non-standard ASV: technical challenges and innovative solutions

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Acoustic seafloor mapping using non-standard ASV: technical challenges and innovative solutions

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Abstract—**The article discusses the use of an innovative Autonomous Surface Vehicle (ASV) developed by CNR-INM for acoustic seafloor mapping. The ASV is modular, portable, reconfigurable, and maneuverable, allowing for low-cost repeated surveys in dynamic areas such as navigation channels and ports. The article describes the challenges and innovative solutions associated with the integration of a multibeam echosounder sensor on the non-standard ASV and describes the first successful test in Venice (Italy) in November 2022. The paper suggests that this system could be a viable solution for accessing and observing shallow waters and difficult-to-reach areas while providing accurate and cost-effective acoustic data gathering for environmental monitoring.**

Index Terms—**Autonomous surface vehicle, acoustic seabed mapping, environmental monitoring**

I. INTRODUCTION

The knowledge of the depth and morphology of the seabed is a key factor in numerous fields of application like environmental protection, cultural heritage, cable and pipeline routing, hydrocarbon exploration, marine litter and pollution observation, biodiversity and ecosystems preservation, underwater geo-hazards, navigation safety, and much more. Despite many years of effort, around 20 per cent of the world ocean's seafloor has been mapped [1]. The morphology of the seabed is obtained by bathymetric surveys mostly carried out by hydrographic vessels that require high costs, and do not operate in very shallow waters or complex coast shoreline scenarios. For these reasons there is a great interest in the research and development of marine robotic vehicles for the study and exploration of areas that are difficult to reach with traditional platforms and that could easily perform low cost repeated surveys in very dynamical areas, such as navigation channels and port areas. A possible solution to access and monitor up to extremely shallow waters is the use of robotic vehicles of the SWAMP family (Shallow Water Autonomous Multipurpose Platform), an innovative highly modular, portable, reconfigurable and manoeuvrable catamaran ASV (Autonomous Surface Vehicle) recently developed by CNR-INM. SWAMP is characterised by small size, low draft, new materials, azimuth propulsion system flushed with the hulls for shallow waters and modular WiFi-based hardware and software architecture [2]. Despite its small size, SWAMP is designed to host numerous series of kits, tools and sensors to perform strategic actions for environmental monitoring, particularly in critical areas. Bathymetric surveys were already carried out in rivers and lakes, using SWAMP equipped with a singlebeam echosounder (SBES) to measure the water depth [3], [4]. However, Multi-Beam EchoSounders (MBES) represents the state of the art technology to collect high precision bathymetric data and achieve high resolution mapping of the seafloor, particularly in lagoons, where sediment transport can impact coastal planning and management and anthropogenic impacts are severe. In the context of the Interreg Italy-Croatia InnovaMare[1] strategic project, a multi-sensory monitoring of the Venice lagoon will be carried out integrating various sensor packages on SWAMP. MBES applications for the morpho-bathymetric reconstruction of the seabed and habitat mapping studies [5] will play a key role paving the way to the capitalisation of project results in other ongoing EC-funded projects, focusing on mapping and removal of marine litter and on characterization of shallow water seabeds, also with the integration of satellite data.

II. MATERIAL AND METHODS: THE CHALLENGES FACED

To integrate an instrument typically used on medium/large boats or vessels on a non-standard and small-sized surface robotic platform, numerous mechanical and technical challenges should be faced, also related to acquisition procedures and data validation. An overview of the mechanical/electrical configuration of the autonomous platform, as well as the integration of the MBES sensor including the software preparation and data acquisition methodology is reported.

A. The Robotic Platform

The need of extremely precise acoustic data gathering translates into the required characteristics of a highly autonomous

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[1] https://www.italy-croatia.eu/web/innovamare/about-the-project

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Fig. 1. SWAMP equipped with MBES, two waterproof boxes for Single Board Computer (green) and Sonar interface module (gray), and two GNSS antenna.

and manoeuvrable robotic platform able to properly perform the intended operations. To this aim, the SWAMP has been adapted and exploited within the InnovaMare project.

The SWAMP is a small-sized catamar-shaped vehicle primary characterized by its mechanical composition, which is based on two twin hulls obtained by a sandwich of foam layers, thus obtaining a stable, lightweight and crash-proof surface platform. The dimensions of the platform are 1.23 m for the length, while the width can be adjusted between 0.70 and 1.25 m depending on the configuration required by the specific operation; the platform weights 35 Kg, with a payload capability of 25 Kg. To enable an agile manoeuvrability, the robotic vehicle is equipped with four independent propulsion modules called *Minions*: each of these modules is composed by a main water pump, responsible for the propulsion force production, and an azimuth motor that rotates the pump nozzle, thus orientating the propulsion force in the desired direction. The propulsion modules are inserted in the hulls (two for each hull) and, once installed, the propulsion modules are entirely contained within the hulls, no moving parts are exposed outside the hull itself, thus reducing the risk of hitting any obstacles or getting stuck. Moreover, each module is equipped with its own battery and a Raspberry Pi computing board that render the *Minion* module a completely modular and wireless unit. Two additional modules complement the overall platform: one is the unit responsible for navigation, guidance and control task, which is an additional cylinder equipped with a Raspberry Pi employed for the required computation and an AHRS (Attitude and Heading Reference System) coupled with a GNSS (Global Navigation Satellite System) based on the Microstrain 3DM-GX3-35 device. A second cylinder equips the platform with a WiFi access-point antenna that allows the connection of all the on-board units, as well as the connection of the remote operator from a ship/ground station for the piloting and supervision tasks.

In order to provide high performance motion capabilities, required for accurate acoustic sampling, the SWAMP is equipped with an advanced control architecture allowing the remote operator to interact with the vehicle at different levels of automation. A low-level thrust allocation module is responsible for the command of water pumps and azimuth motors in such a way to provide the desired overall propulsion force. This goal can be achieved in different operational conditions, such as transfer motion or hovering, where the geometric configuration of the thrusters are set differently. The control architecture provides tasks for the heading and speed regulation, thus enabling course-defined navigation and constant cruise speed transfer (nominally ranging from 0.5 to 1.0 m/s, while the maximum speed is up to 1.6 m/s, but the navigation precision is degraded). Furthermore, advanced guidance methodologies are developed and exploitable as way-point navigation, with the vehicle performing a line-of-sight based motion towards a desired point of interest, and line-following allowing the tracking of geo-referenced linear transect. This latter approach is of suitable use during acoustic data gathering with MBES, providing a constant motion over rectilinear transects with compensation of lateral disturbance, i.e. the optimal condition for acoustic data sampling.

A complete data logging, provided by the navigation system, allow to aggregate the payload information (the MBES samplings for this specific application) and the vehicle functional telemetry. In post-processing, it is then possible to georeference the acquired data, as well as correct them through attitude and velocity compensation.

B. Hardware Integration

The MBES system is a R2Sonic2020 I2NS: its highly portability, compactness, lightness and low power consumption make it particularly suitable to be mounted on an autonomous vehicle. The instrument is provided as an integrated solution including the wideband multibeam echosounder, an Inertial Measurement Unit (IMU), a Sound Velocity Probe (SVP) from Valeport, two GNSS antennas, the Sonar interface module

(SIM), a power inverter, and all the needed cables that were crafted at the appropriate length.

The entire R2Sonic multibeam echosounder and Applanix POS/MV integrated system weighs less than 7 kg (Sonic2020 head + IMU) and fits into a single carrying case, making it easy to integrate. A Multi-Purpose (MP) box was designed and built to host, boot, control, and power the Single Board Computer (SBC) which is connected via Ethernet to the SIM and via wi-fi to the remote control PC. The SBC runs the QPS Qinsy 9 software for data acquisition and display as well as quality check during acquisition, and needs to be connected to the internet to receive the Real-Time Kinematic (RTK) corrections. The SIM is contained in a second box, together with the inverter, and the batteries. Such a box is located next to the MP one on top of the movable structure situated in the middle of SWAMP, as shown in Fig. 1. All other components (IMU, SVP, and the Sonic head) are installed on a vertical movable structure, located between the hulls, that allows the sensors to be located at different depths. All instrumental offsets are measured referred to Centre of Gravity (COG). It can be assumed that the IMU position is the COG. This structure is covered by foam hydrodynamic structure to protect the instruments, facilitate the navigation and reduce the effect of flow turbulence and bubbles on the signal. The soft-foam also provides a buoyancy reserve to support the weight of the submerged sensors. Two GNSS antennas are installed on an aluminium structure fitted along the vehicle's longitudinal axis, holding them at the required height above the water level and sufficiently distant from each other to ensure good positioning data. A centimetre-level positioning accuracy is ensured by RTK correction. In the presented survey, an RTK-RTCM3 format is used for real time position correction.

C. Acquisition procedures and data validation

In order to obtain accurate and reliable seabed acoustic data, it is necessary to carry out a sequence of operations before the acquisitions. These operations consist in the precise measurement of the offsets between the various components of the system and in the calibration of GNSS antennas and MBES. The details of the operations performed are described below.

Offset measurements

Multibeam offset (measurements referred to the COG and using Qinsy sign convention): x= - 0.118 meters, y= - 0.045 meters, z= - 0.167 meters. Offset primary antenna (measurements referred to the COG and using Applanix sign convention): x= - 0.955 meters, y= 0 meters, z= - 0.90 meters

GNSS antenna calibration

In order to perform the GAMS (GNSS Azimuth Measurement System) calibration, SWAMP was maneuvered through moderately sharp turns (8-shaped path and s-turns) incorporating changes of speed and direction, until the GAMS solution was calculated. The result is the exact position (in terms of x, y, z) of primary antenna relative to the secondary one. This is the result in our test (Applanix sign convention): x= 1.599 meters, y= 0.004 meters, z= -0.013 meters

MBES calibration

A multibeam calibration must be performed to measure the angular misalignment between the MBES head and the motion sensor and gyro and, if necessary, the position latency; this is called the Patch Test. A measurement of the water column sound velocity was taken and added to the software before starting the patch test. MBES calibration was performed using two sets of lines acquired at 320 and 400 kHz, on a well-known bathymetry in Venice Arsenal, this because the patch test requires collecting sounding data over two distinct types of sea floor topography; a flat bottom is used for the roll computation whereas a steep slope or feature is used for the latency, pitch, and yaw data collection. The resultant patch test values are corrections that will be entered in the post-processing software (QPS Qimera).

MBES Acquisition

A first successful data acquisition campaign was carried out in November 2022 in Venice (Italy), demonstrating the system capability by performing fast high-res bathymetry inside the Venice Arsenal (Fig. 2), where the depth ranges between 4 and 6 meters, and in the San Pietro-Certosa dock, where the depth ranges between 3 and 10 meters, in gentle breeze sea state and high tide. The first area is a sheltered small internal basin, characterized by the presence on the averagely flat seafloor of large abandoned ballast weight with average dimensions of 3.5 x 3.5 m and 0.5 m in height, mostly squared in shape. The second area is located in the dock area of the Certosa Island, characterized by intense boat traffic and located in a channel separating the northern and southern part of the Lagoon, where seabed morphologies, between 0.1 and 0.7 m high, indicate different patterns of bottom currents and erosion paths. The SWAMP was maneuvered following straight parallel lines guaranteeing full overlap in swath coverage.

The biggest innovation for R2Sonic multibeam is the possibility to select in real-time on the fly from between 170 - 450 kHz to 1 Hz resolution, along with optional ultra-high resolution (UHR) 700 kHz. Moreover, with Multimode it's possible to capture data at different frequencies simultaneously. The beamwidth is variable with frequency being 1° x 1° at 700 kHz; 2° x 2° at 400 kHz; 4° x 4° at 200 kHz. The multimode acquisition was tested in the San Pietro-Certosa dock acquiring data simultaneously at 220, 320, 400 and 700 kHz. **MBES Processing**

The MBES data were post-processed using the software QPS Qimera for batimetric data and FMGT QPS tool for backscatter data. All measurment are corrected using tide values taken from Venice tidegauge station published on national tidegauge network (www.mareografico.it).

III. PRELIMINARY RESULTS

The data collected were processed and analyzed in order to evaluate the possible connections between the guidance, navigation and control performance of the non-standard and small dimension ASV and the quality of the final acoustic MBES data.

Regarding the navigation precision, the efficiency of under-

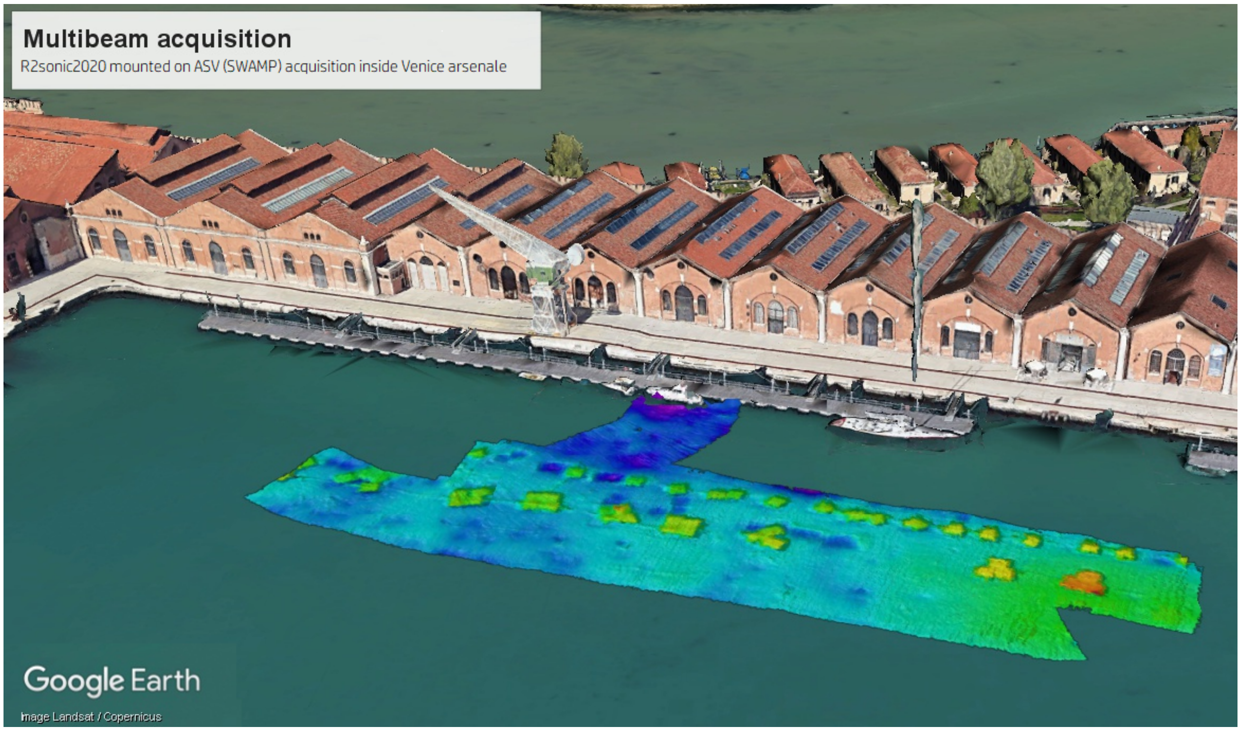

Fig. 2. 3D view of the multibeam acquisition inside the Venice Arsenal, DTM resolution 0.1 m.

water measurements and the quality of data is reduced if the running line is not straight. The program-based automatic control of SWAMP accurately corrected the direction and position of the vessel in real-time and allowing, for example, the correct imaging of the squared anchorages that are very well resolved in terms of geometry.

To investigate in more detail the links between SWAMP motion and MBES acoustic data, two acquired swath sections are reported in the following, depicting the MBES images collected over rectilinear transect autonomously executed by the SWAMP in the San Pietro-Certosa dock area.

A first acoustic data collection is reported in Fig. 3 where the sea-bottom morphology, ranging from about 3.2 to 3.9 m, along one single transect of motion is recreated through a post-processing data analysis, carried out by means of the Qimera software. An overlapped "segmentation" effect over the morphological map can be observed, with a number of tiny shadowed cross-lines appearing all over the map. This effect can reasonably be attributed to the presence of a wave disturbance, slightly affecting the motion of the vehicle; the components of this wave-induced disturbance can be observed in the pitch and roll data reading from the AHRS device, depicted in Fig. 4. Sinusoidal signals in the range of 2 to 4 degrees of amplitude, with a peak at 6 degrees, are read from the AHRS indicating the presence of waves in the test scenario. Even though the post-processing software is fed with the attitude signals, it is not able to completely compensate and filter the effect of the disturbance, resulting in the slight presence of the "segmentation" in the image. In order to mitigate at best the wave-induced disturbance, a mechanical solution, i.e. mounting the MBES on a gimbal stabilized platform, can be advised and will be investigated in future developments.

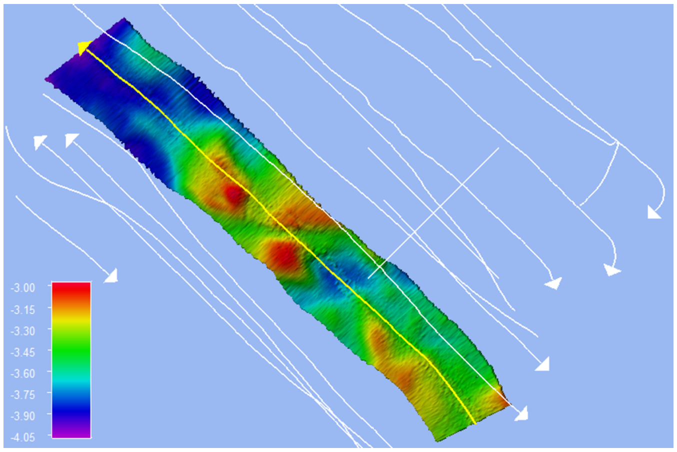

Fig. 3. Swath 1 - Morphological acoustic map.

An important analysis to be carried out, with respect to the autonomous motion of the robotic vehicle, is the evaluation of the orientation of the vehicle (namely the heading, i.e. the orientation of the platform longitudinal axis) with respect to the desired course (i.e. the direction of the rectilinear transect to be tracked). In an ideal environment, the execution of the sampling mission would lead the heading of the vehicle to have the same exact value of the reference course; this

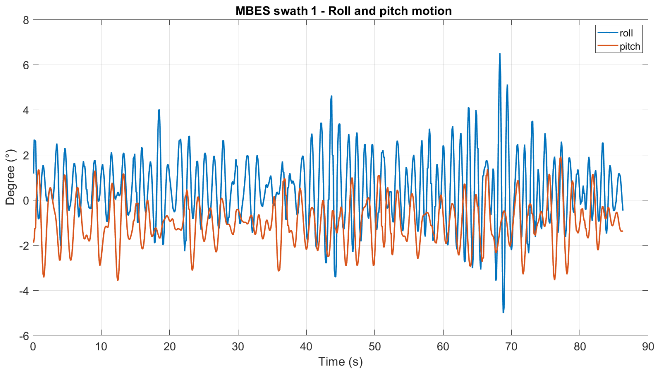

Fig. 4. Swath 1 - Roll and pitch motions of SWAMP along the rectilinear transect.

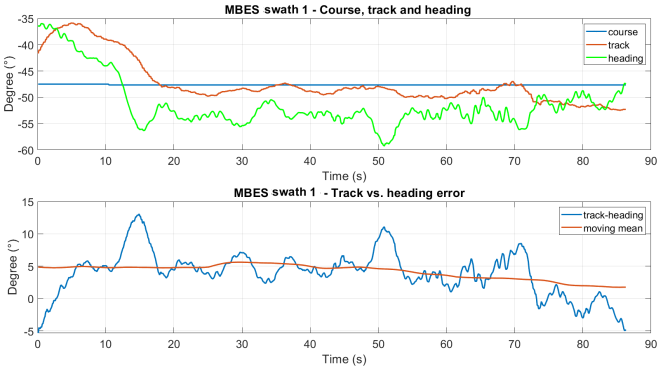

Fig. 5. Swath 1 - Course, track and heading of SWAMP along the rectilinear transect (top) and slip-angle evaluation (bottom).

also represents the optimal operating condition for the MBES system which requires the acoustic swath to be perpendicular to the direction of motion. Unfortunately, sea currents are usually present in real operating scenarios and leads the robotic vehicle to modify its motion pattern in order to compensate for such disturbance. Along-currents (i.e. sea currents directed along the orientation of the longitudinal axis of the vehicle) are not a major concern, since they only affect the speed of the platform, that can be anyway mitigated by a robust auto-speed regulator. Cross-currents (intended as the sea currents perpendicular to the vehicle orientation) deviate the vehicle from its track (the direction of motion) that is no more parallel to the heading of the platform itself. The line-following guidance system onboard the SWAMP is developed in such a way to trim the vehicle's heading to align the track to the intended course; the result is that, in order to move along the reference transect, the vehicle will be crabbed and, accordingly, also the MBES device, leading to a non-optimal data gathering. This behavior is shown in Fig. 5 where, in the upper plot, the course (reference transect direction), track (vehicle motion direction) and heading (vehicle orientation) are compared; the lower plot reports the difference between the track and the heading, also known as the compensating slip-angle. It is possible to notice the presence of an almost constant slip-angle of about 5 degrees, apart for local glitches due to disturbance compensation.

Since the SWAMP is a fully actuated platform, thanks to its thrust mapping characteristics, a scheduled improvement will be the development of a sea-current regulator system based on a suitable orientation of the thrusters (by commanding the azimuth motors), in such a way to compensate the cross-current components without requiring the vehicle to assume a slip-angle; in such a way, the MBES data acquisition can be executed in the almost optimal condition.

A second representative data set and its corresponding swath coverage of the sea bottom is reported in Fig. 6 to show the behavior of the vehicle in relation to the result of the data acquisition process. During this acquisition the roll and pitch motions (Fig. 7) were slightly more intense with respect to the previous one, reflecting with shadowed ripples in the bathymetric map, in particular where the roll and pitch peaks reach 6-8 degrees of amplitude (it has to be remarked that the operating scenarios was also beaten by the presence of boat traffic that could have generated small local waves).

The track and heading measurements of the vehicles are depicted, with respect to the intended course, in Fig. 8, as well as the slip-angle, with a decreasing value from about 15 to 5 degrees, probably due to the local environmental changes given by natural and anthropic structures present in the area (e.g. sediments on the seafloor and piers surrounding the area).

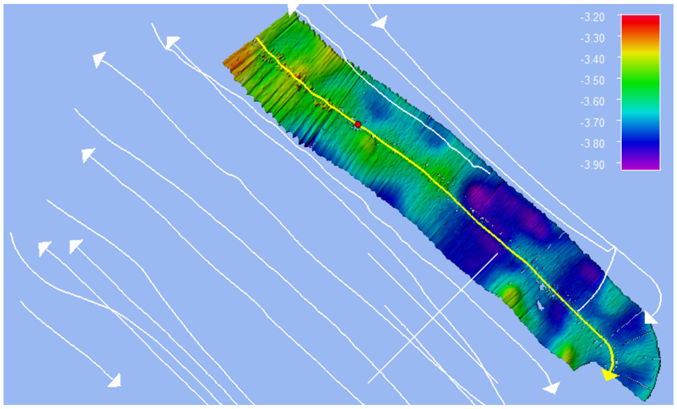

Fig. 6. Swath 2 - Morphological acoustic map.

DISCUSSION

Bathymetric measurement operations in very shallow waters (few meters of depths) are often difficult because of tidal ranges and harsh environment that make these areas unreachable by conventional vessels, as safety of navigation is seriously reduced. Since unmanned marine vehicles, such as ASVs, can be remotely operated by pilots from safe locations, they are suitable for operations in dangerous areas, by virtue of their advantages of a lightweight, less load and shallow draft. Moreover, users can design and save track lines in the navigation system so that the ASV can intelligently control its navigation based on high-precision position and speed information, thereby performing highly repetitive monitoring

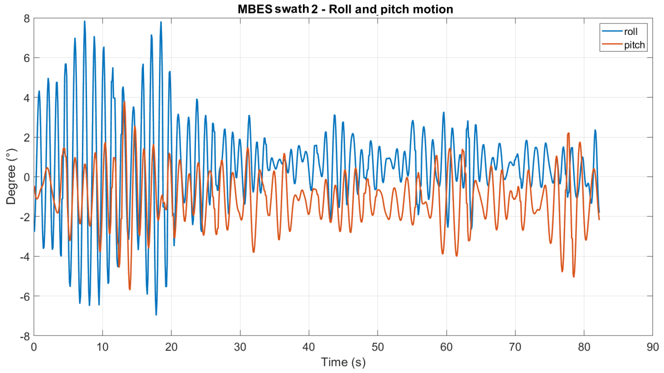

Fig. 7. Swath 2 - Roll and pitch motions of SWAMP along the rectilinear transect.

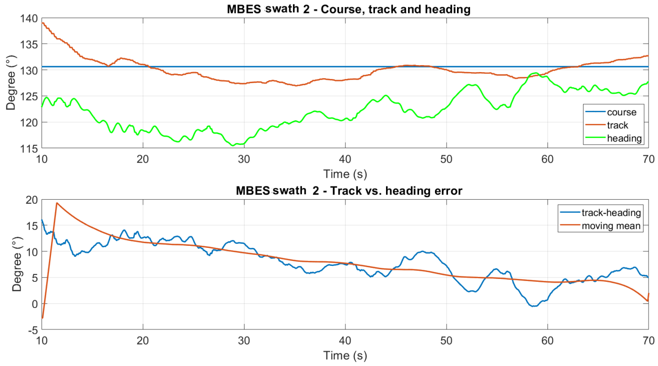

Fig. 8. Swath 2 - Course, track and heading of SWAMP along the rectilinear transect (top) and slip-angle evaluation (bottom).

tasks. However, ASVs have to incorporate efficient automatic navigation control technology to follow the planned route in such complex working environments, with different speeds and changes in tidal flow direction, winds and waves occurring also in a short time frame that often need a re-planning of the survey on the fly. A major difficulty to overcome in underwater topographic surveying operations is therefore to keep up with the complex water environment. As the navigation mode may affect the quality of a survey, with options ranging from joystick control by operator to fully autonomous navigation without any supervision [6], different modes of navigation will have to be investigated more in detail in future surveys. In addition, also the testing of a suite of algorithms to enable depth constrained autonomous bathymetric mapping by SWAMP will have to be implemented. As an example, an implementation would be to have a target depth and a bounding polygon for the SWAMP to cover and achieving complete seafloor coverage inside the polygon (e.g. [7]).

The accuracy of collected data is directly dependent on the precision of automatic guidance, which, in turn, is influenced by the availability of the RTK service providing high-precision GNSS measurements, and even a small deviation in navigation direction can affect the acquired data and the quality of the final result, as shown in the previous data analysis. Ensuring a stable network connection to retrieve RTK correction is crucial for obtaining high-quality acoustic data, even during sea tests. However, RTK signal loss has been identified as a recurring issue that needs to be addressed in future field tests to improve survey operations. In the unfortunate event of RTK absence, a suitable positioning estimation/filtering module has to be included in the overall architecture, in order to mitigate the navigation degradation. Near term developments are intended to provide advanced navigation modules. The feature of geo-referenced motion control of the ASV combined with high-precision navigation capability aims at reducing the motion error below the standard value of 20 cm. A full RTK coverage would realistically provide a centimetre-scale accuracy.

The MBES integrated on SWAMP proved to be a successful and effective survey solution for operational scenarios where commonly manned vessels are hindered. The quality of the acquired data proved to be comparable with data-sets provided by standard sampling procedures. For such a reason, the employment of a small-sized autonomous robotic platform is particularly suggested in a scenario like the Venice Lagoon, since the very shallow water characteristics may dramatically impact the quality of the data gathered, as well as the operational activities, for instance in low tide periods, where manned vessels are unable to work. Moreover, implementing advanced control systems and stabilization technologies will be a further step for the enhancement of the collected data, as well as an improved reliability of the platform itself.

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