Potentialities of integrated 3D surveys applied to maritime infrastructures and to the study of morphological/sedimentary dynamics of the seabed

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Abstract – **The potentialities of an integrated 3D remote sensing survey with the most diffuse techniques, i.e. photogrammetry from UAV, laser scanner and multibeam from survey boat, are enhanced. Such techniques are useful both to verify the state of conservation of maritime infrastructures from a structural point of view and to highlight the phenomena of erosion or accumulation of sediments at the base. The case study relative to the breakwater of the "Porto Sole" private tourist port and the seabed facing it along the Sanremo coast (Imperia, Italy) is shown. The produced 3D model at centimetric resolution both of emerged and submerged areas describes the maritime infrastructure and allows to recognize and measure the seabottom forms. Hence, it results a valid aid for the study of morphological and sedimentary dynamics of the seabed.**

I. INTRODUCTION

Remote sensing techniques are widely used to acquire a huge amount of data in a quick way in order to reconstruct the 3D model of objects, structures and coastal landscapes. In the maritime and coastal environment, the most diffuse ones are photogrammetry from UAV (Unmanned Aerial Vehicle) and multibeam integrated with laser scanner from survey boat [1-7].

In addition to these consolidated techniques, new ones are tested [8,9]. Among these, laser scanner from UAV (usually called LiDAR, i.e. Light Detection and Ranging) or from underwater ROV (Remotely Operated Vehicle),

satellite photogrammetry to reconstruct the bathymetry, underwater photogrammetry mainly to survey structures or objects on the seabed. Also inertial sensors and elaboration algorithms, such as SLAM (Simultaneous Localization and Mapping), are improving. However, some new solutions are still too expensive, some others are not yet consolidated and therefore result unsuitable for commissioned surveys.

The integration of photogrammetry from UAV with multibeam and laser scanner from survey boat was experienced by the authors in different contexts. It results useful both to verify the state of conservation of maritime structures from a structural point of view and to highlight erosion and accumulation of sediments at the base. The potentialities of the integration of these techniques are enhanced in the following section II.

Then, a case study is presented (section III), where such techniques are applied to a limited sector of the Sanremo coast (Imperia, Italy) relative to the breakwater of the "Porto Sole" private tourist port and the seabed facing it.

The produced 3D model at centimetric resolution both of emerged and submerged areas allowed also to recognize, measure, orient bedforms and sedimentary accumulations, as described in section IV. Therefore, these measures constitute a valid aid for the study of the geomorphological and sedimentary response of the seabed to the action of wave motion and the currents generated by topographic forcing, in areas with relevant anthropogenic modifications [10-13].

II. POTENTIALITIES OF INTEGRATED 3D SURVEYS

From the in-field experience of the authors, the potentialities of an integrated 3D survey using photogrammetry from UAV, multibeam and laser scanner from survey boat are here highlighted.

The authors believe that multibeam technique is currently unrivalled to map underwater areas. However, if the goal is the survey of both the emerged and submerged areas, the best solution is a system integrating laser scanner and multibeam mounted on a survey boat. Obviously it has to be equipped with the ancillary instrumentation, i.e. an Inertial Platform and a GNSS-RTK (Global Navigation Satellite System in Real Time Kinematic) to obtain the position with a centimetric accuracy. This system is the only certified one; moreover, the acquisition is easy and automatic, the outputs are metrically reliable and provided in a short time (1 day). On the other hand, the instrumentation is not cheap and expert operators are required to setup and calibrate the system, to acquire, analyze, filter and process data. When the coastline is inaccessible from land, as in the case of cliffs, such integrated system is mostly necessary.

Moreover, the integration of the topographic and bathymetric surveys gives continuity to the final 3D model, framed in the reference system defined by the GNSS-RTK. The real time detection of the emerged and submerged surfaces referred to the 0 mid-sea level (msl) is guaranteed by the aforementioned integrated system. In fact, the survey conditions are usually variable over time; the mean level may vary slowly or quickly due to controlled or uncontrolled events, e.g. the effect of tide variation on the sea or the filling or emptying processes on lakes or basins. If the survey lasts a few hours and the water level is locally below zero, this is detected by the laser scanner, while the multibeam is not be able to observe it. If the survey is prolonged for several days and/or the areas of interest have consistent level excursions, the detection of the surfaces above or below zero level is difficult employing just one of the two techniques. These different possibilities are represented in Fig. 1, where the dashed line represents the reference zero level and the continue line represents the tide level changing in time. The "minus" sign indicates the area not surveyed by the considered technique, whereas the "plus" sign represents the surveyed area. Hence, the integration of both instruments results fundamental.

Moving to the photogrammetric technique, the current great advantage is the low cost of the instrumentation and the semi-automatic processing, that leads even less experienced users to try it.

The photogrammetric surveys, recently mostly carried out by UAV, can provide a useful integration to the 3D laser scanner model by survey boat, usually having different points of view: the laser scanning from the sea, the photogrammetry from the nadir on the area of interest. By means of photogrammetry it is possible to reconstruct the 3D model of the environment surveyed by SFM (Structure From Motion) processing. However, to achieve a photogrammetric 3D model comparable to a laser scanner one in terms of accuracy and precision, more attention is needed in planning the survey and positioning of an adequate number of well distributed Ground Control Points (GCPs), as well as a high computational effort [14,15].
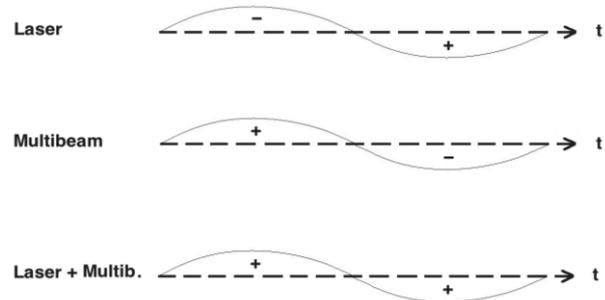

Fig. 1. Area surveyed (+) or not (-) by the different techniques during tide evolution.

The authors consider photogrammetry more useful if carried out in a "medium" or "expeditious" mode to obtain the radiometric information for the surveyed area, or as a refinement of the laser model in poorly covered areas, thanks to the high-resolution camera mounted on UAV. On the contrary, the laser scanner survey can support photogrammetry in the a posteriori identification of natural GCPs, with a consequent lower cost in terms of time and effort to place and survey them, especially in inaccessible areas, such as location where protection rocks or blocks are present. Even in the port environments, an optimal spatial distribution of GCPs can be challenging, given the usually elongated geometries of the structures. In order to obtain a correct framework scaled in local coordinates system, a good number of GCPs has to be placed on two or more alignments, i.e. one along the breakwater and the others parallel to it.

Additionally, the radiometric information acquired by photogrammetry is useful to solve any doubt about metric data collected by laser scanner. In fact, if information is available on the objects that have interfered with the survey, it is possible to better detect and distinguish the anomalies (which can be removed from the point cloud) from the instrumental noise (which can be better filtered out).

The radiometric information is also useful to highlight particular themes of the area under study, such as the state of degradation of asphalt (of particular interest around the bollards), walkways and docks, the position of signs, water columns, moorings, parking spaces, and islands of demarcation between road and pedestrian area. This information could also be used to create or enrich a GIS (Geographic Information System) for the management and maintenance of the port area. Finally, the photographic documentation helps in the drafting of technical specifications for construction or demolition, where the description of the port-city context from the geometric point of view is necessary.

Photogrammetry is not particularly useful for identifying precisely the exact boundary between emerged

and submerged areas, because this boundary can vary even in the short period and sometimes the reflection of natural light on the sea does not permit recognition and correct measurement. On the contrary, the identification of erosion or deposition areas on a beach sometimes can be facilitated by analyzing the color acquired by photogrammetry. Sometimes photogrammetry is able to reconstruct even submerged areas, if the water is clear and steady. In this case, the point cloud is generally only reliable in the first few meters underwater, due to both the refraction and reflection phenomena that affect more for higher depths and to the lack of GCPs in the water.

A case study is shown in the following section.

III. CASE STUDY AND METHODS

The sector of the Sanremo coast (Imperia, Italy) was formerly featured by a narrow fluvial-coastal plain formed by the alluvial deposits of Foce, S. Romolo, S. Francesco and S. Martino streams and by the materials deriving from the sea cliff erosion and landsliding of Capo Nero Promontory. Within the last century, the relevant urbanization and the construction of port settlements caused widespread erosional phenomena affecting all the beaches, due to the reduced solid contribution from watercourses.

In fact, since the beginning of the 20th century, the reduction in the depth and width of the Sanremo beaches has been very marked, as a result of the construction and modification of the "Porto Vecchio" and subsequently, in the period 1975-1980, of the construction of "Porto Sole" [16,17]. These phenomena have been counteract by the construction of several soft and hard coastal defense works.

The study focuses on the breakwater of the "Porto Sole" private tourist port and the seabed facing it (Fig. 2).

The site was surveyed on February 2019 by means of an equipped survey boat and a camera mounted on UAV.

The boat was equipped by the Teledyne Reson PDS2000 platform, for the simultaneous acquisition of a MultiBeam EchoSounder (MBES) R2Sonic 2024, a Sound Velocity Profiler (SVP) RESON mod. SVP-15, an Inertial Measurement Unit (IMU) IXBLUE mod. HYDRINS III, a mobile Laser Scanner (MLS) RIEGL mod. LMS-Z420i used in profiler mode and a GPS 5700 TRIMBLE receiver in "rover" Real Time Kinematic configuration (GPS-RTK). The MBES R2Sonic 2024 is characterized by 256 beams of $(0.5°×0.5°)$ and $(1°×1°)$ across and along track beamwidth at 400 kHz and 200 kHz, respectively. In order to investigate the portions of the bottom close to the free surface, the transducer was mounted on a joint angled at 25°, thus physically tilting the transducer to exploit the entire swath of the MBES. The MBES/MLS systems required a preventive calibration phase both to synchronize the time scale of each instrument (comprising IMU) and to compensate Roll, Pitch and Yaw angles of the system with respect to the theoretical (0,0,0) point, called CRP (Common Reference Point). Data of both instruments were processed by the software platform Teledyne Reson PDS2000 [18].
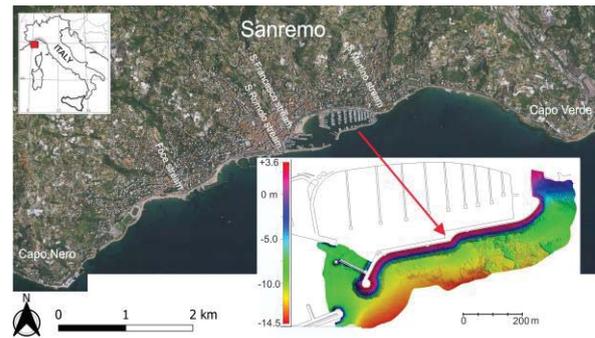

Fig. 2. Sanremo and the "Porto Sole" breakwater.

Particular attention was paid to the removal of the background noise (despiking) and to data filtering, essential for the automatic/semi-automatic noise removal in water column, often caused by navigation motion and reflections of some types of structures geometries. Seabottom morphology results are represented with high-resolution DTM (Digital Terrain Model) and DSM (Digital Surface Model) with variable resolutions of $(0.1×0.1)$ m - $(0.25×0.25)$ m, depending on client's request.

The employed laser scanner is RIEGL mod. LMS-Z420i, a TOF (Time of Flight) instrument, characterized by 1 km maximum range and a repeatability of 8 mm on a single measurement and 4 mm on average in static 3D configuration. In mobile profiler mode, precisions varies between 2 and 5 cm, depending on distance of targets and objects measurement and quality of IMU (angular precisions). MLS data are also processed by the software platform Teledyne Reson PDS2000. In the present case, precision in the order of 2-3 cm was obtained, measured and compared both with Total Station and GPS-RTK data.

UAV Photogrammetry was performed through a 20 MPx camera mounted on DJI Phantom 4 Pro. The flight height was set to 35 m, resulting in a GSD (Ground Sample Distance) of 7.2 mm. The overlapping between images was set to 80% for both longitudinal and transversal directions. The resulting 1148 images were processed by means of the photogrammetric suite Agisoft Metashape© [19] producing a 3D point cloud.

The multibeam, laser scanner and photogrammetric point clouds have been integrated and the continuous DSM both for emerged and submerged zones was built at a 0.1 m resolution.

To assess their quality, the MBES, MLS and UAV resulting point clouds have been compared in a test overlapping area, the head of the pier of "Porto Sole". The comparison and the following elaborations have been performed using the free and open source software CloudCompare [20].

An estimate of the overlapping area has been carried out, firstly considering two point clouds at a time (MBES+MLS, MBES+UAV and MLS+UAV), then also the overlapping area of the three point clouds has been computed. In Fig. 3a the overlapping point clouds are shown. The common area between the three techniques is very limited (1.37 m²). The overlapping area between

MBES and MLS or UAV is limited too (about 7 m^2 and 6 m^2, respectively) and localized along a strip near the 0 mid-sea level, having the techniques a different point of view on the pier head. On the contrary, MLS and UAV overlap on a significant portion of the structure (about 548 m^2).

A DSM with (10×10) cm cells resolution has been computed from each point cloud (Fig. 3b-d). The DSMs allow to calculate the per-cell populations and the height standard deviations for the three point clouds. The results are reported in Table 1, together with DSMs maximum and minimum values.

Table 1. Averaged per-cell populations and height standard deviations for MBES, MLS and UAV DSMs.

DSM	Average per-cell population [-]	Average heights std [m]	Minimum height [m]	Maximum height [m]
MBES	5	0.074	-12.58	1.03
MLS	6	0.067	-4.72	15.15
UAV	48	0.036	-1.60	4.91

The per-cell population represents the number of points falling in a cell of given dimensions (10×10 cm in the present case), thus it can give a rough indication of point cloud density. The UAV DSM has a higher average value of per-cell population (48), whereas MBES and MLS DSMs have lower and comparable values.

The heights standard deviation measures the dispersion of height values inside each cell: the smaller is its value, the more homogeneous are the heights. It results that MBES and MLS DSMs have similar values (0.074 m and 0.067 m), showing a substantial comparable distribution of heights in the point clouds. The UAV DSM has a lower heights standard deviation value (0.036 m), also probably due to the more flat surveyed area (the pier emerged part).

The maximum and minimum height values show how MBES has surveyed also the area 1 m over the 0 mid-sea level, UAV 1.5 m below and MLS even 4.5 m below, even if the result is quite noisy. MLS was also able to survey a metallic lighthouse and three flagpoles in their height, while UAV nadiral survey and processing were not able to reconstruct them. Being the overlapping between MBES and MLS or UAV limited, only the MLS and UAV DSMs have been compared in each cell. This has been done deploying the CloudCompare's M3C2 plug-in [21], which allows to obtain signed distances in the vertical direction between two point clouds. The result is shown in Fig. 4a.

The average value and standard deviation of the differences (UAV-MLS) are 0.049 m and 0.397 m. The higher differences are due to three flag poles and the small metallic lighthouse (A and B in Fig. 4a, respectively), which generate positive distances between the two DSMs. On the contrary, the negative distances (C in Fig. 4a) are due to cars which were present only during the UAV survey.
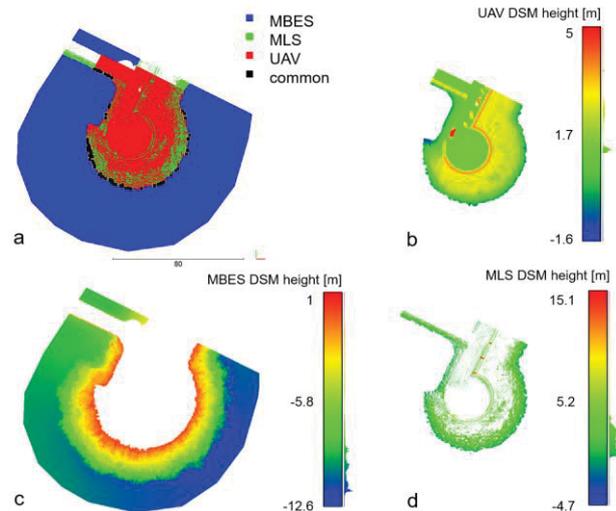

Fig. 3. Overlapping area at the head of the pier of "Porto Sole": overlapping point clouds (a), DSMs from UAV (b), MBES (c) and MLS (d) and statistical distributions of height values (next to the scale bars).
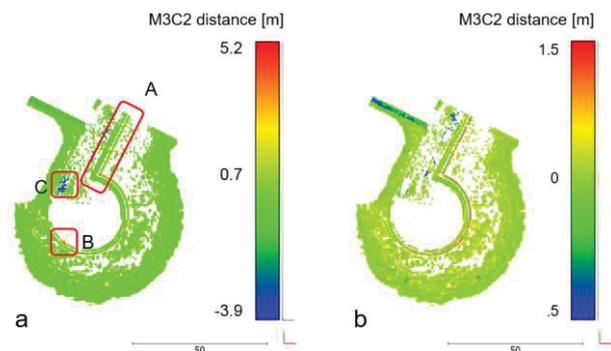

Fig. 4. Difference between UAV and MLS DSMs heights with (a) and without (b) outliers.

Apart from these areas, the two point clouds are very similar, as shown in Fig. 4b, where the higher differences have been filtered out. After the outlier removal, the average value and standard deviation of the differences (UAV-MLS) are equal to 0.062 m and 0.265 m, respectively. The higher differences are located along the perimetral wall of the breakwater (Fig. 4b); this can be due to the different point of view of MLS and UAV over the structure.

Finally, the three point clouds have been compared along a significant section to analyze their altimetric behavior (Fig. 5). The section highlights the already mentioned overlapping and the substantial continuity, demonstrating that the integration of the three techniques has been properly conducted. A focus has been performed on the perimetral wall (zoom A in Fig. 5), to show the discrepancy between MLS and UAV point clouds along the inclined wall and the better results on vertical ones, due to the different point of view of the two techniques.
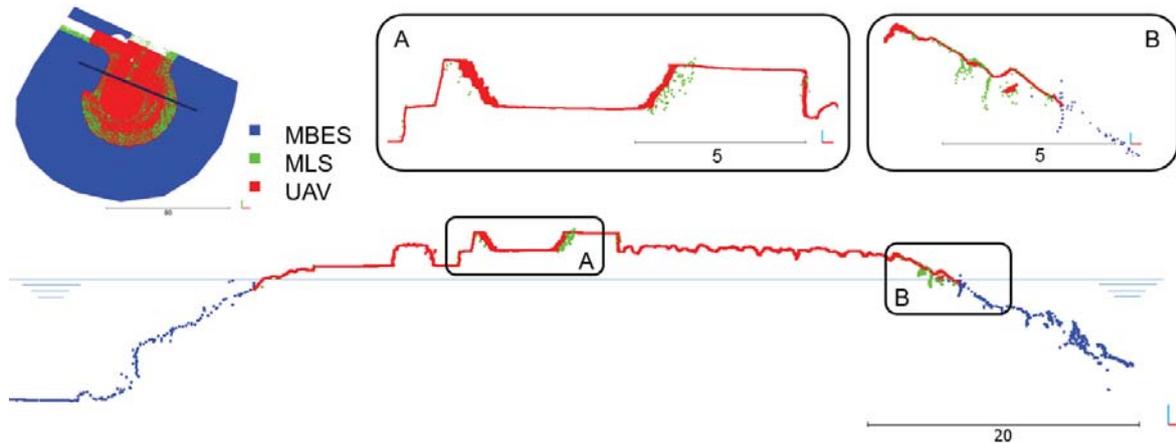
Fig. 5. Section of the three point clouds and focus on the perimetral wall (A) and on the 0 mid-sea level (B).

The focus on the 0 mid-sea level (zoom B in Fig. 5) enhances the substantial continuity of the three point clouds, even with some residual noise in the boundary between emerged and submerged areas.

IV. HINT ON MORPHOLOGICAL AND SEDIMENTARY DYNAMICS OF THE SEABED

Considering that the "Porto Sole" private tourist port is part of a coastal stretch with a generalized erosive trend, the survey of the breakwater has been conducted in order to highlight instability phenomena both of the maritime structures and of surrounding seabed. In relation to the SW-NE orientation of the breakwater, the dominant sea wave motion (220°) reaches the structure with low angle, while minor wave motion from 140° reaches the structure almost perpendicularly. The S. Martino stream, located immediately to the East of the root of the breakwater of "Porto Sole", does not contribute with sufficient volumes of sediment to the stability of the coast and in particular to the nourishment of the small pebble beach between the mouth of the stream and the breakwater of the port.

The integrated survey highlighted some very peculiar aspects in the sedimentary dynamics of the seabed and of the beach just Eastward the breakwater (Fig. 6). In particular, it is noted that waves from Libeccio (SW-220°) generate a transport of sediment to the coast, evidenced by the presence of ripples/megaripples marks facing the coast, whose wavelengths range between 0.4 and 1 m. The refraction of the Libeccio waves and the almost frontal impact of the Scirocco waves determine an accumulation of sediments on the emerged beach, with the coarsest residual granulometries on the extreme East of the beach and the finest granulometries (always included in the gravel) on the West side, more protected by Libeccio. The setup generated by the incident waves on the beach causes a return current on the seabed, that erodes two channels between the base of the breakwater and the base of the artificial ridge on the right bank of the mouth of the S. Martino stream. In the central-western sector of the seabed in front of the breakwater, residual deposits of dead matte of Posidonia oceanica and Cymodocea nodosa in strong

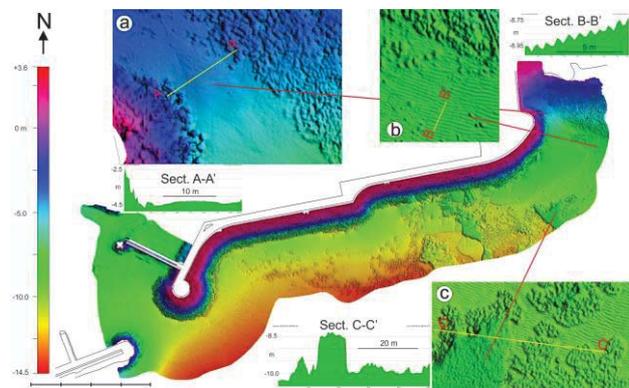*Fig. 6. Focus on characteristic areas of the submerged 3D model: a) accumulation; b) ripples/megaripples; c) dead matte of Posidonia oceanica and Cymodocea nodosa.*

erosion have been also identified.

The port infrastructure substantially modified the dynamics of the sediments in the nearby areas, being an obstacle to the sedimentary flows of the waves of Scirocco (from SE) and Levante (from E), with a consistent reflection of the wave motion on the overhang, not allowing the finer fractions to settle at the base of the infrastructure. The erosive trends and the possible axes of transit of the sediments on the seabed, in addition to the identification of marine biocoenosis present on that stretch of seabed, were possible thanks to the integrated survey of breakwaters and in front of the seabed.

V. CONCLUSIONS

The integration of MBES, MLS and UAV techniques has been tested to survey the "Porto Sole" private tourist port. Particular attention has been given to the comparison of the three techniques on a portion of the breakwater. It allowed to quantify the overlapping area, assess the centimetric accuracy and evaluate the continuity and coherence of the point clouds; moreover, it highlighted weak and strength points of each technique. The integration of the three techniques seems the optimal

solution. Finally, the point clouds deriving from the integrated survey resulted useful to investigate and describe the sedimentary and morphological dynamics of the seabed, also in view of a future maritime infrastructure design to contrast the instability phenomenon.

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