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Combined Acoustic and Video Characterization of Coastal Environment by means of Unmanned Surface Vehicles

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Abstract: The aim of this work is the exploitation of an Unmanned Surface Vehicle (USV) for visual and acoustic characterization of the seafloor in shallow water coastal environments, through combined acquisition of echograms and video images. To this purpose, the employed vehicle is composed by two systems: *i*) a leading USV, equipped with an advanced mission control architecture, which performed a grid sampling over the study area; *ii*) a towed vehicle hosting an integrated system for acquisition of video and ultrasonic images, from the water column and the seafloor, coupled with a GPS receiver, which provided the geo-referencing of the survey. Data acquisition was carried out over different seafloor types, which included rock outcrops and sediments (mostly sand). The main key-points of employing such techniques to this peculiar field of coastal area monitoring are the possibility to perform automated missions and the capability to operate in very shallow water areas, usually not accessible to conventional boats.

1. INTRODUCTION

Environmental monitoring of marine and oceanic areas is a fundamental step in order to guarantee sustainability and maintenance of ecosystems and habitats. These tasks are common for many fields of applications (including the evolution of flora and fauna habitats and their changes in response to natural or anthropogenic changes, and the study of marine erosion and deposition processes, which control redistribution of sediments along the coasts) and need to be evaluated at different time-scale to suggest strategies for coastal maintenance. Other fields of interest include detection of mineral deposits or morphological formations such as reef, underwater valleys, thermal vents, as indicators of geological processes that shape the seafloor in a given environment. More in general, identification of physical and biological connections is the key action to enhance policies of effective environmental management. In fact, the multidisciplinary knowledge of the natural environments (in particular the coastal environment), which is poorly investigated, heavily impacted by human activities and prone to ecological crises, could guide protection schemes based on effective exchanges between protected areas; the European Project COCONET [1] is the actual framework whose main goal is the actual framework whose main goal is the definition of guidelines to design, manage and monitor network of Mediterranean Protected Areas (MPAs).

Cultural aspects related to underwater archeology are also of great interest and include the discovery of ancient artifacts, settlements or ship wrecks, as well as the protection and maintenance of already known archaeological sites.

For such reasons the continuous exploration and monitoring of underwater areas is an important task, which deals mostly with observation and characterization of shallow water areas. For instance, monitoring and safeguard of Posidonia sea grass is of valuable interest; Posidonia meadows represent the ecosystem with the highest biodiversity in the Mediterranean Sea, providing also the most effective oxygen supply to superficial waters. Monitoring of erosion and deposition of marine sediments in coastal areas is fundamental to carry out effective maintenance, such as installation of protective barriers or sand replenishment.

One of the most difficult tasks to be achieved is the periodic observation and sampling of such areas, because monitoring technologies are expensive if performed onboard conventional oceanographic vessels. The introduction of a robotic technology can overcome the problem of assigning repetitive, tedious and expensive tasks to human operators, when such goals can be easily achieved by the employment of highly autonomous marine platforms. Furthermore the access to many interesting shallow water areas is usually dangerous or even impossible to conventional vessels or boats; small robotic platforms characterized by a very small draught could access such difficult marine areas, reducing the risk of grounding.

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[1] http://www.coconet-fp7.eu/

Many studies and researches focusing on seafloor characterization can be found in the literature. The work in Waddington and Berman [2007] reports a method for benthic habitat characterization. This work, after a brief overview of a proposed acoustic technique used to generate an initial broad-scale characterization of the seafloor, presents a detailed survey of the sediment-profile imaging technique that can be used as an efficient high-resolution tool for ground-truthing the broad-scale acoustic data.

In Tsemahman et al. [1997] a 50 Hz echo sounder combined with a digital wave form acquisition system and a seabed classification software were used to record and process echoes from a bay southeast Vancouver Island, Canada; each echosounding was preprocessed and several statistical and spectral algorithms were used to extract characteristic patterns. In Penrose et al. [2005] a review of the acoustic techniques for identification, classification and mapping of benthic habitats is given, as well as a report on the commonly employed acoustic devices and subsurface sensing techniques. The unmanned marine robotic vehicle ROAZ, developed by the Instituto Superior de Engenharia do Porto, has been employed for bathymetric surveys in Ferreira et al. [2009]; the aim of this work was collecting data for risk assessment in shallow water environments and water-land transitional zones. The employment of an Unmanned Surface Vehicle (USV) for automatic bathymetric survey is also presented in Yanfeng et al. [2011], furthermore including an adaptive isobath environmental profiles tracking. The task of collecting bathymetric data through autonomous vehicles in very shallow coastal, estuarine, and inland water environment is performed by means of a Small Waterplane Area Twin Hull (SWATH) vehicle, described in Kitts et al. [2012], which provides natural platform stability for a multibeam sonar payload.

The aim of this paper is to present how the robotic technology represented by the Unmanned Surface Vehicles (USVs) can be effectively employed for biological or geological observation and data acquisition of the coastal environment. In particular, the work focuses on the employment of a double vehicle system, composed by a leading vehicle in charge of navigating along a predefined sampling grid, towing a trimaran-shaped platform equipped with video and echosounding devices. Video equipment is employed to observe and characterize the seafloor environment, recognizing sandy and rocky areas, evaluating area extension of flora habitats, locating polluting objects and so forth. The echosounding device is firstly exploited to obtain a bathymetric map of the working area; through the analysis of raw acoustic signals and echo reflections and analyze reflectivity pattern as diagnostic of different seafloor types.

The test site for this combined visual and echographic survey was a shallow water coastal area ($< 7m$) close to Murter Island (Croatia). Although, in general, such surveys are devoted to simply estimate the seafloor depth, digitally sampled echogram were used to infer the acoustic properties of the seafloor, i.e. the normal incidence reflectivity. An acoustic wavelet generated at the sea surface is partly reflected and scattered at the sediment/rock-water interface, and partly transmitted in the sub seafloor, generating further reflection within the marine sedimentary sequence. The returning echo contains components of the transmitted pulse with backscattering components (see Hamilton [2011]). Typically, a flat and smooth seafloor may have a high percentage of energy reflected back to the transducer, resulting in a trace with narrow peak with no tail. Conversely a rough, complex seafloor may have high degree of scatter, and traces could show peaks and tails.

Nature of echoes are influenced by many aspects of seabed topography such as grain size parameters and the presence of benthic fauna and flora. All physical characteristics of the reflected acoustic waves depend on these properties. Analysis of such echoes may be crucial to determine physical and biological nature of the seabed. This direct analysis of the seabed needs to be calibrated and ground-truthed by direct measures. Usually direct sampling of seabed is used for this purpose.

In this work, together with echosounding data, pictures of seabed were collected using an underwater camera, which allowed to qualitatively estimate the relationship between ultrasonic echoes from the different seafloor types. Rate of picture acquisition and echosounding were synchronized in order to have a perfect correspondence between positioning of the two data-sets.

The paper is organized as follows: Section 2 includes a description of the employed robotic platforms and sensors, as well as a brief outline of the mission definition and execution; Section 3 describes the mission design and execution for video and acoustic data gathering, exploiting an autonomous robotic platform; the results obtained by the data collection are reported and described in Section 4; conclusions and discussions on future steps are given in Section 5.

2. ROBOTIC SYSTEM

The combined sampling of video and acoustic data described in this work has been carried out through the employment of a dual robotic platform system. It is composed by: *i)* the leading vehicle CART USSV, originally developed within the European Project CART for ship towing operation support tasks (an extensive description is reported in Bruzzone et al. [2013]); *ii)* the towed trimaran-like sampling platform, equipped with video and acoustic devices, that will be transformed into an autonomous surface vehicle in a short-time upgrade.

In the following of this section the characteristics of the two employed platforms will be described.

2.1 Leading vehicle

The CART USSV, developed by CNR-ISSIA and reported in Figure 1, is a 0.9 m long and 0.75 m wide robotic platform. The thrust is provided by four DC brushless motors coupled with 4-bladed propellers, capable of a maximum bollard pull of about 15 Kg. A central cylindrical canister contains all the computation and sensing electronic devices; in particular, the USSV is equipped with a single board computer running a GNU/Linux based real-time control application, a GPS system providing the absolute position fix and an AHRS (Attitude and Heading Reference System). Another cylinder contains a set of Lithium ions batteries providing energy for the vehicle for $5 \div 6$ hours of operations.

For the goal of exploiting the CART vehicle as a testbed for the development of advanced navigation, guidance and

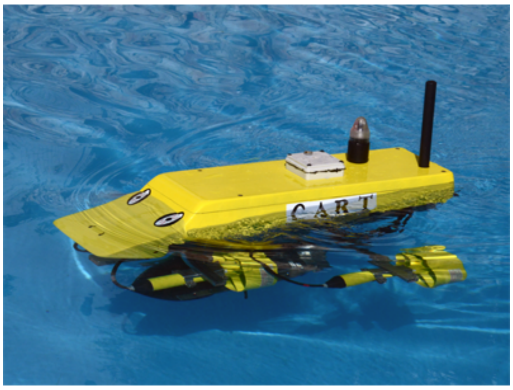

Fig. 1. CART USSV during operations

control techniques, as well as payload carrier in different experimental campaigns, the software control architecture as been upgraded porting an already extensively tested and exploited system. In particular the control architecture of the CNR-ISSIA Charlie USV has been customized to be also able to run on the CART USSV. The porting operation basically regards the development of a new *driver* layer, thus creating the connection between the hardware and logical variables; all the higher levels of the architecture do not require any adaption, because of the complete decoupling from hardware-related issues. In such a way the high level mission definition and execution module of the Charlie USV (described in Bibuli et al. [2008]) can be exploited to autonomously drive the CART USSV along an area coverage grid.

The mission control subsystem is a high level module allowing the user to define and execute a completely customized mission plan. The key issue of this mission control architecture is the high level of interaction between the user and the mission controller itself. Apart from an off-line mission plan definition, the user is allowed to reconfigure or adapt the mission specifics during the on-line execution. A human operator can add or update desired paths or motion primitives, as well as control reference variables, e.g., cruise speed. Moreover the mission behavior can be adapted as a function of environmental condition occurrences or user commands, triggering the execution or the replanning of parts of the original mission plan. This can be provided thanks to the intrinsic modular design of the mission control module, which is composed of three main elements: i) data structures, from simple ones like booleans, integers, or real variables, to more complex ones like lists, queues, or stacks that can be used, for example, to store waypoints or reference paths to be followed by the vehicle; ii) execution actions, like simple Petri nets whose marking defines the actual state of the action, linked with semantic modules that specify the primitives or commands related to the specific execution action; iii) control flow modules, also named containers, representing the topological interconnection between the execution actions and thus the execution flow, as for instance series, parallel, selection and iteration flows. In the remainder of this section, a custom mission for a maritime security application will be designed. In this kind of framework, the operator covers the role of the mission supervisor, monitoring the vehicle's state, evaluating time-changing operative condition (that can arise due to environment, traffic, unexpected situations) and (semi-)automatic on-line mission replanning or adaptation. The strong interaction between the human operator and the autonomous system, yields the robotic platforms to be very effective tools in such a kind of applications.

2.2 Towed platform

The trimaran-shaped sampling platform is a robotic vehicle currently under development at CNR-ISSIA. For the task of a preliminary campaign of coupled video and acoustic data gathering, it was decided to exploit the still non-actuated platform mounting on that the video and acoustic devices, then linking the platform to a leading vehicle with the task of towing the sampling platform.

The trimaran-shaped sampling platform reported in Figure 2, has a hull characterized by 1.20 m of length, 0.8 m of width and 0.2 m of height (excluding electronic box and antenna pole) dimensions. A single board computer running a GNU/Linux based real-time application collects the data gathered by the video and acoustic devices (mounted on the stern bottom side of the vehicle and thus not visible in the picture) and integrates them with a geo-referenced fix obtained by a GPS system. The video acquisition system is based on an underwater camera, rigidly mounted on the USV hull, that was initially exploited for mosaicking operations of shallow water seafloor by means of an USV Ferreira et al. [2012]. The chosen camera is characterized by low weight ($32g$) and small dimensions (44 cm x 44 cm x 25.4 cm) implied neither a decrease in resolution (Wide-VGA with 752 x 480 pixels) nor a low frame rate (maximum 87 fps). The USB connection that serves as both power and data transmission erases the need of a separate power source. The lens used is an 8 mm one. The focal length as well as the camera parameters were calibration using a chessboard and the MATLAB® Camera Calibration Toolbox.

Fig. 2. Trimaran sampling platform during pool trials

A vertical incidence echosounder, the PSA900 manufactured by Datasonics, was used to collect ultrasonic images of the water column and the seafloor. The PSA900 is particularly suitable for shallow-water environments because is characterized by a high operating frequency (200 kHz), a narrow (8 , conical) beam width, a short pulse length (350 sec), and a minimum depth range of 0.75 m. The 200 kHz echosounder signal was digitally within a constant time window, and the data (the echograms) were stored in SEGY-format files (Barry et al., 1975).

3. DATA COLLECTION MISSION

Relying on the mission definition and control architecture of the employed autonomous vehicle, an usual sampling mission (represented in Figure 3) over a lawn-mower sampling grid has been defined.

Once the sampling grid has been defined (by setting desired position, orientation, width, length and number of transects), in the first phase of the mission all the geometrical trajectories are computed and stored into an internal data structure. As the main mission loop starts, each reference transect is loaded and the vehicle is commanded to track it through a proper path-following algorithm (refer to Bibuli et al. [2009]). The reference path is tracked until the end of the actual transect is reached or if the remote human operator decides to switch to the following reference line. The mission is completed when all the reference sampling transects have been executed. A simplified example of the motion of the vehicle executing the sampling mission is reported in Figure 4, where it is possible to notice the good tracking capabilities, keeping into account that the area was subject to wind and sea current and that the leading vehicle was mostly affected by the towed platform during the navigation. As shown in the picture, the vehicle, navigating at a speed of about 0.4 ÷ 0.5 m/s, assumes an orientation in such a way to compensate the effect of the external environmental and towing-induced disturbances.

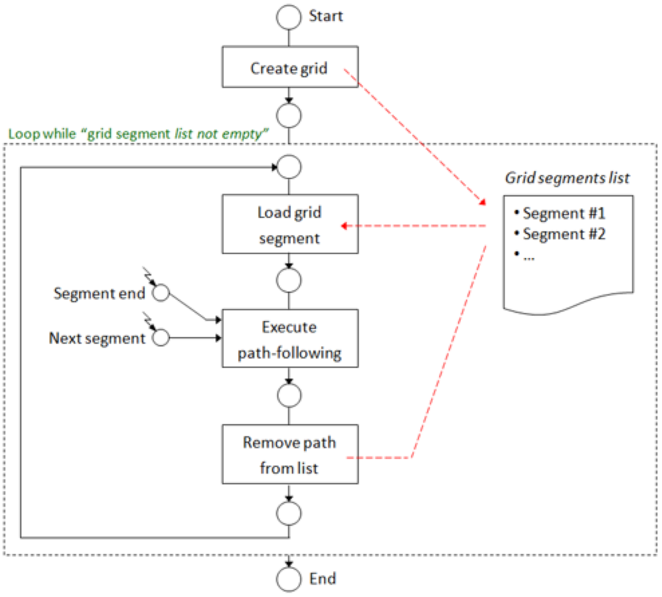

Fig. 3. Mission scheme for autonomous data collection

4. COLLECTED RESULTS

The first step of data processing was to estimate water-depths from the raw echograms. To this purpose, the procedure described in GASPERINI 2005 was followed, computing an amplitude envelope trace by convolving the squared values of the original data trace with a rectangular window of the same width of the source pulse. Conversion of travel-times into water-depth was performed assuming a constnt sound velocity of $1500 m/s$. The acquisition of the entire echogram at each sounding point, rather than the simple depth estimate, gives the opportunity to calculate. In the case of vertical incidence, neglecting the effect of energy scattering due to the bottom roughness, it is possible to calculate the reflection coefficient (R) using: $R = \frac{A_y}{A_s} z$ where A_r and A_s correspond to the amplitude of the source and reflected signals respectively, and z is the water depth. In order to obtain an estimate of R from the finite-length echosounder pulse, A_s and A_r are expressed as:$A_s = \sum_{i=0}^{W} |x_i|$ and $A_r = \sum_{i=B}^{B+W} |x_i|$ where x_i represents the digital sampled signal, W is the width of the source pulse and B is the bottom detection time. Once reflectivity data were obtained a comparison between reflectivity patterns and video imaging of the seafloor was performed. In fact although seafloor reflectivity is dependent on several physical and biological aspects, such as colonization by plants and animals, diagenesis, etc. an interesting matching between reflectivity and seafloor geological properties (such as mean grain size of the sediment) has been observed in similar shallow-water environments without visual inspections (e.g. Gasperini 2005). Echograms were collected in depths ranging from $1m$ to $7m$ over different environments characterized by sandy, rocky, or mixed seafloor types. Digital sampling of the ultrasonic signal was performed at constant sampling rate ($NS = 10000$) while the ping rate was 8 per secon. In this way an acquisition time window of $8ms$ per ping was obtained, corresponding to a depth of $6m$, assuming a constant sound velocity of 1500 m/s. Echosounder profiles shown in figures 5 and 6 were obtained using Seisphro, an interactive computer program for processing and interpreting high-resolution seismic reflection profiles (Gasperini and Stanghellini [2009]).

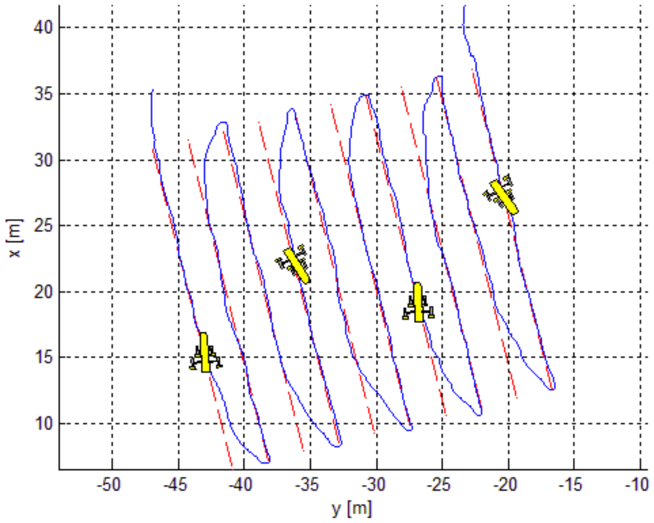

Fig. 4. Leading vehicle motion during lawn-mower mission execution

This data representation is obtained by plotting signal amplitude during propagation time (y-axis) vs shot number, represented on the x-axis. Amplitude of the ultrasonic signal is displayed as colour variations along the y-axis. The two profiles presented in figures 5 and 6 are a selection of 1500 pings collected using the same acquisition parameters, allowing a qualitative comparison between different

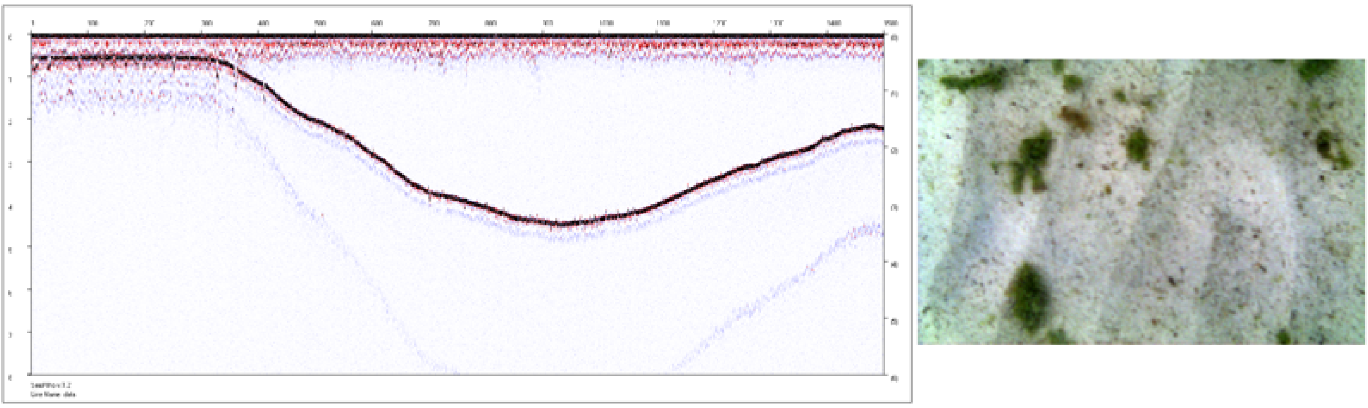

Fig. 5. Left: example of echographic profile in sand-dominated seafloor. Right: video image collected in the same area

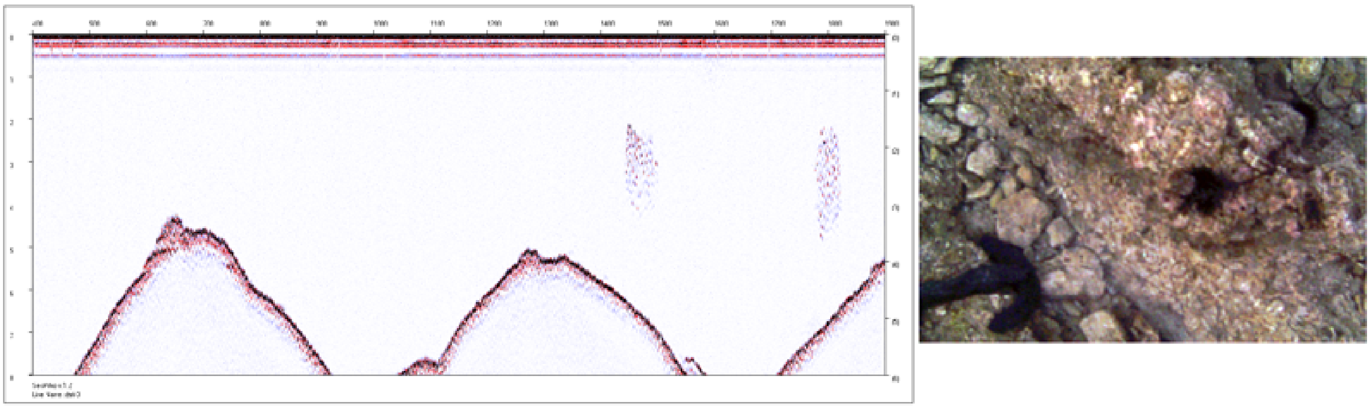

Fig. 6. Left: example of echographic profile in rocks-dominated seafloor. Right: video image collected in the same area

acoustic responses of the seafloor, in terms of reflectivity and morphology. We assume that the intensity of the reflections from the seafloor is related to physical characteristics (density and sound velocity) of the media. By this simple approach it is possible to carry out a general qualitative analysis of seafloor types. However, since an estimate of the reflection coefficient at the seafloor was performed, this qualitative observation could provide a quantitative evaluation of reflectivity coefficient represented by R. Figure 5 displays an echogram obtained in a homogeneous, sandy seafloor. We observe a smooth morphology of the principal reflector representing the seafloor and relatively low values of R. This ultrasonic pattern is ground-truthed by underwater imaging, which show in correspondence of relatively low R values a smooth, sandy, homogeneous seafloor. A different ultrasonic pattern is observed in figure 6. This profile shows a high degree of signal scattered and reflected from the seabed, with a more marked reflector, characterized by a complex morphology and the reflector is generally thicker. This setting corresponds to higher average values of R and a more "patchy" variability of seafloor reflectivity. It suggests the presence of a rocky seafloor, as confirmed by analysis of video imaging (figure 6). In Figure 7 an echogram characterized by composite pattern (rocks and sand) is shown; pictures aside the acoustic profile are related to the points marked in the echogram. Every point corresponds to a set of about ten pings (echoes) and every ping is related to nearly about six pictures collected with the camera.

In this profile (figure 7) characterized by high lateral variation of seafloor reflectivity, the areas characterized by sandy or rocky seafloor are marked by an numbered arrow, which corresponds to a picture to the right of the echogram. The normalized seafloor reflectivity is plotted at Figure 6 bottom.By the compared analysis of reflectivity and video imaging of the seafloor, we note that higher reflectivity values correspond to the rocky seafloor, while the sandy, relatively smooth, areas show lower values. The good fit between ultrasonic and visual imaging enable us to future extension of this techniques to a compositesuite of seafloor types, producing a catalogue of case histories that could cover the geological/biological variability of the costal environment. This could be eventually used in cases where visual inspection are not feasible due to the absence of light or the presence of light-scattering particles in the water column.

5. CONCLUSIONS

These preliminary tests of combined echosounder and visual seafloor observation suggest the possibility of using such techniques to perform habitat mapping of the seafloor in shallow-water environment using Unmanned Surface Vehicles. nvestigate seabed composition directly from echograms. One of the future development will include the analysis of the seabed response in terms of reflectivity, backscattering and frequency analysis, to extract wave parameters that can be linked to physical properties. Comparison between underwater images and echograms

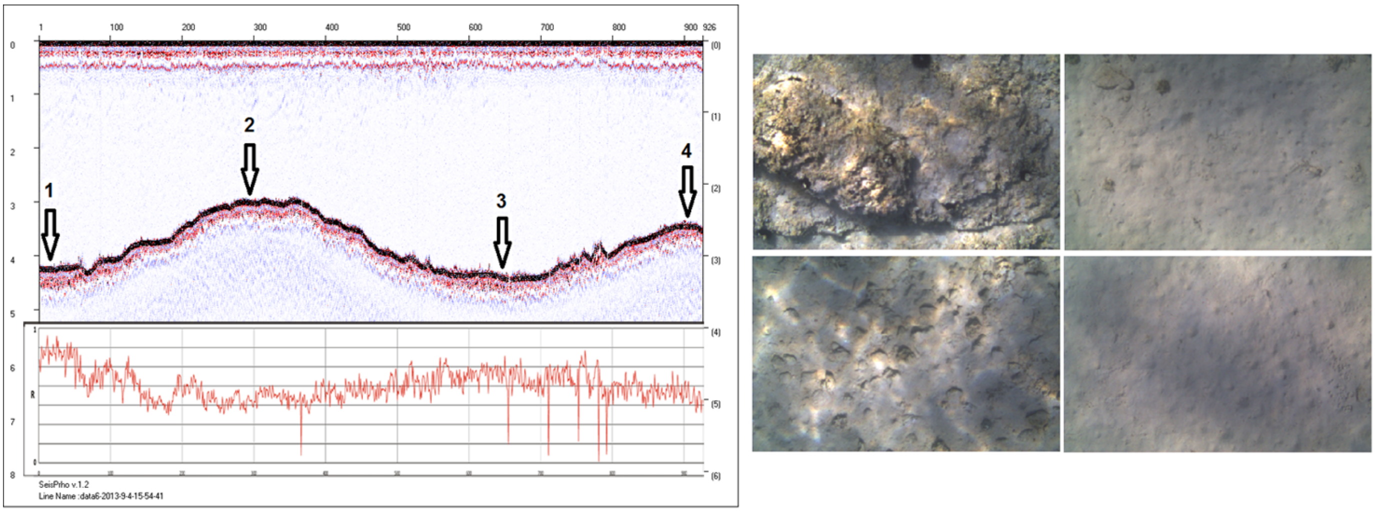

Fig. 7. Echogram of the seafloor across different domains. Numbered arrows indicate the location of seafloor pictures collected at any given point. Reflectivity curve (red line, figure bottom) shows that higher R-values correspond to a rocky seafloor.

allowed to test the combined video and echosounding acquisition system and constitutes a first step to develop methods of nearly real-time analysis of seabed morphology. This work has shown the effectiveness of autonomous robotic platforms for monitoring the shallow-water coastal environment, relying on an advanced automatic mission execution system. Finally the real-time(or quasi real-time) knowledge of bathymetry and seafloor profile can be exploited to feed the mission execution system and carry out adaptive missions to detect a particular seafloor pattern or a given marine habitat.

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