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Enhancing autonomous capabilities and human-robot interaction for Unmanned Surface Vehicles

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Abstract— **In the context of autonomous exploration and observation of water areas by means of Unmanned Surface Vehicles (USVs), this work describes the improvements developed with respect to the advanced mission control system and the integration with multiple and modular sensing devices, in particular underwater cameras and sonar systems. The experimental proof of the concept validity is obtained testing the overall framework on the CNR-ISSIA Charlie USV. Moreover, to enhance the interaction capabilities between human operator and autonomous platform, different driving and commanding devices, including multi-purpose reconfigurable console and smartphone applications, have been developed and integrated with the already existing architecture. Data gathered from the experimental campaign carried out in Murter (Croatia), within the "Breaking The Surface 2011" training field, are reported.**

I. INTRODUCTION

In the last two decades USV (Unmanned Surface Vehicle) technology has maturated, providing a wide number of technical solutions for the most spread application scenarios. In fact, USVs are very efficient and low cost robotic platforms easily exploitable for a number of autonomous applications, such as exploration and observation, restricted area protection like coastal or harbor zones, environmental data gathering and sampling, as described in [1] and [2]. An extensive employment of this class of robotic vehicles has also been devoted to maritime security applications as patrolling and target detection and identification in restricted areas, and also for MCM (Mine Counter-Measure) operations [3], with the aim of localizing possible treats in the target area, e.g. in the work [4] where a pan-tilted multi-beam sonar device was mounted on the Charlie USV and commanded from a remote station. Moreover, being USVs the interface between water and air environments, they are often used as communication relays between underwater robots, such as ROVs (Remotely Operated Vehicles) or AUVs (Autonomous Underwater Vehicles), and remote control station, as proposed for instance in the pioneer EC funded ASIMOV project [5].

The exploitation of USVs perfectly fits with applications for very shallow water areas, where it can be possible to employ both video and acoustic sensor devices to explore, observe and characterize the surrounding environment. Operating in shallow waters, the deployment of an USV dramatically reduces costs and logistic efforts with respect to ROV and AUV operations. Secondly, a reliable wireless or radio link between the USV and remote control station allows the user to online monitor gathered data, thus adapting the USV operations and/or system parameters in order to optimize the mission results [6].

Regarding the use of vision systems in USVs several examples can be found (especially on the military field) but practically all of them include above surface cameras and not underwater cameras. For instance, in [7], an omni-directional camera is used to map the shoreline. A vision-based docking system with a USV and a floating AUV is described in [8] and obstacle avoidance is performed in [9].

In order to provide the human user a reliable tool, capable of exploiting video and acoustic payloads, automatic guidance and control modules and mission supervision systems are developed for USV platforms. In particular, in the recent years, huge efforts have been devoted to the development of the most various advanced mission control and supervision systems [10],[11]. The goal of this work is to present the recent improvements developed for the CNR-ISSIA Charlie USV with respect to the autonomous capabilities enhancement, introduced by the employment of an advanced mission control system able to satisfy autonomy mission specifics, providing a high level of interaction with the human user as well. This work is focused, in particular, on the mission design and execution oriented to the exploitation of an underwater camera system for automatic mosaicking of the seabottom, also allowing the online supervision of the network quality-of-service (QoS) and the quality of the data gathered, which is fundamental for optimizing data collection. In addition, the paper proposes different technological approaches for human-machine interaction, including a custom multipurpose reconfigurable console and a novel interaction approach based on the development of smartphone applications to improve the user's "easy-to-use" feeling

The paper is organized as follows: in Section II an overall description of operative scenarios as well as main desired

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requirements for a vision-based exploration & observation mission are provided; then a general description of the mission control system is given, focusing on the design and execution phases. The onboard integration of complex sensing systems is reported in Section III, while the introduction of new devices for human-machine interaction is presented in Section IV. The experiments are detailed in Section V while some conclusions are drawn in Section VI.

II. MISSION CONTROL SYSTEM

The mission control system 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, developed in [12], 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 online 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 triggering the execution or the replanning of parts of the original mission plan. This is provided due 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 way-points or reference paths that the vehicle will have to follow; 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 visual exploration surveywill be designed. The operator's task is to focus on the contacts and tracks on the geographic display, and the classification quality sensor data on the auxiliary display. The operator has precedence over the autonomous decisions, but his/her input should remain at a high level, indicating only what should be placed in the field-of-view of the sensors. The resulting mission can, thus, be summarized as: i) performing autonomously a lawn-mower like inspection of an extended area; ii) when the user detects a point of interest or a general target, the vehicle has to interrupt the exploration, switching for instance to a circular motion around the specified target. Referring to Fig. 1 where the mission plan is depicted, the first step is the computation of the reference segments of the lawn-mower grid. The mission controller computes the transect segments of the lawn-mower grid, when grid parameters are sent from the remote user station. In particular, the grid is defined by:

- (x_G, y_G): coordinates of the center of the grid with respect to a fixed reference frame,
- ψ_G: orientation of the parallel transect segments,
- (W, L): width and length of the grid respectively,

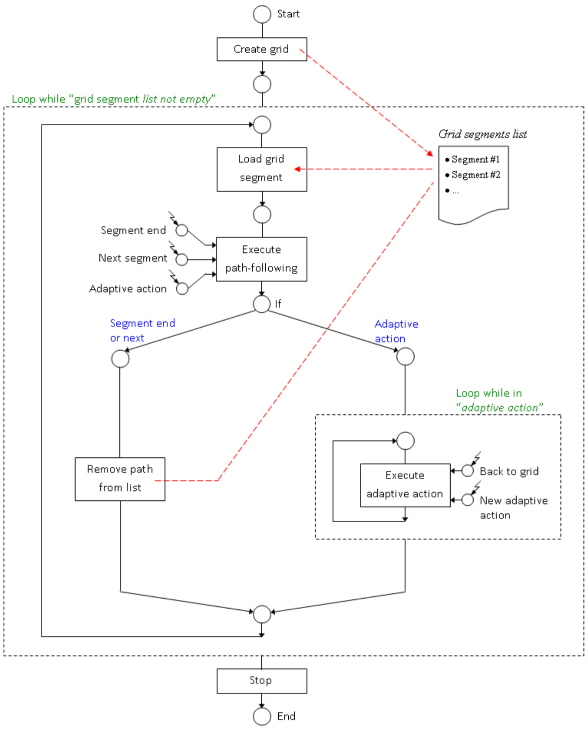

Fig. 1. Petri net scheme of a basic adaptive mission.

- N: number of transect segments.

Moreover, taking into account the minimum curvature radius of the vehicle steering, the line references for the parallel transects are connected with minimum curvature radius arcs, allowing the vehicle to start each transect with the correct tangent [6]. Transect segments and connecting arcs are then stored in the proper grid segment list data structure. The rest of the mission is contained in a loop: at each loop occurrence the grid segment at the top of the list is loaded and used as a path reference. The guidance system of the vehicle will perform the path following until the end of the current segment is reached or the system receives from the user the command to switch to the next segment. Thus the actual reference is removed from the list and, at the next iteration of the loop, the new reference is loaded repeating the process. Another event that can interrupt the execution of the path following operation is the occurrence of an adaptive action request, i.e. an user request for a custom survey. The user can force the vehicle to track a particular point, sending a command from the remote interface, specifying the coordinates of the target points, radius and speed of the circular tracking manoeuvre. The vehicle indefinitely moves around the specified target point until the user requires the recovery of the autonomous inspection. On such command occurrence the mission controller recovers and loads the last active grid segment and restarts the lawn-mower like inspection. The mission ends when the vehicle has covered all the specified grid, i.e., all the reference segments have been followed.

III. NEW SENSING SYSTEMS ONBOARD

A. Underwater camera

A very innovative aspect of this work is the underwater camera connected to the hull of the USV. As far as the authors could find, there is no other USV with a similar approach. The motivation for this feature has to do with successful work done in real-time mosaicking of the seafloor using a ROV navigating near the seabed described in [13]. Obtaining a rough still usable mosaic of the seabed in real time allows the operator (in the ROV case) or the end-user (in the USV case) to plan and adjust missions during the mission itself. For instance, if after a first mission, some object or other kind of interesting feature (from the biological, archeological points of view e.g.) is identified, the user can easily see in a visual map where the object is located and plan a new mission that goes back to the same point. Although real time mosaicking for marine applications has not captured the attention of a large community of researchers (in opposition with offline mosaicking), the recent PhD thesis of Kristofer Richmond [14] gave a significant contribute. Therefore, this area of research should be deepen and the possibility of applying it to surface vehicles investigated. In the case of the USV, the tested area should be shallow waters as with a fixed camera the quality of the images degrades with depth even in clear and transparent waters.

The integration of an underwater camera aboard a USV involves the development of hardware (mechanical and electrical) and software modules in order to guarantee effective data acquisition, registration, synchronization with the vehicles telemetry and monitoring of QoS. Moreover, in order to not compromise the whole mission, the camera should be a payload as much uncoupled as possible from its vehicle. The integration basically consisted of the following steps.

1) Electro-mechanical integration, including the custom-made underwater canister for the camera, a support for a laser system and installation aboard the vehicle of a dedicated single board computer;
2) Implementation of a Data acquisition and control system (DACS) responsible for:
    - acquiring, merging and logging of the raw image data and basic USV telemetry
    - compressing the images in JPEG and sub-sampling them for transmission on low bandwidth channels;
3) Development of a device Graphical User Interface, that allows the end-user to monitor the QoS, set the transmission and compression parameters and more important tuning the camera parameters like exposure time and others.

The implementation of this idea started with the choice of the camera. The relative cheap chosen camera has several characteristics that are worth to be mentioned. The low weight ($32g$) and the small dimensions ($44cmX44cmX25.4cm$) do not imply a decrease in resolution (Wide-VGA with $752X480pixels$) neither a low frame rate (maximum $87fps$). The USB connection that serves as both power and data transmission eliminates the need of a separate power source.

In previous works [15], a Laser-Triangulation Optical Altimeter proved to be a reliable estimator of the depth in the context of near sea bottom ROV navigation. Hence, a similar system to that one was mounted together with the camera as shown in Figure 2. Nonetheless, an echo-sounder mounted next to the camera, provides also depth measures as the laser system might have some problems due to illumination issues.

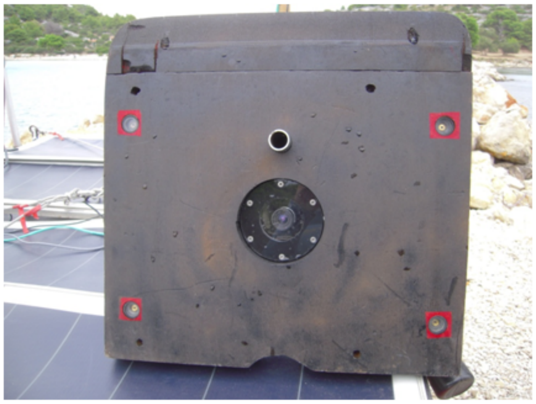

Fig. 2. The camera mounted together with the laser system

A very simple though extensive interface was developed and all the camera parameters plus the compression and subsampling rate of the JPEG images sent from the USV to the Land PC can be controlled on that interface. A JPEG image is available to the end-user in real time providing valuable feedback for the tuning parameters process. The full control and communications scheme for the vision system is illustrated in Figure 3. The control interface allows to change the parameters of the camera which affects both the logged BMP images (raw data) and the JPEG images sent to the PC at land. It is through these received JPEG images that the user can assert the quality of the data being logged and adjust the camera parameters. The user has also the knowledge of the bandwidth consumed by the JPEG images and can adjust accordingly the compression, size and sampling rate in order to guarantee QoS for the other applications running on-board and communicating with the mainland station. All the communications between the vehicle and the land PC are performed using the UDP[1] in order not to compromise other vital communication modules, something that could happen if TCP[2] was used due to its management of lost packets.

B. Sidescan sonar

Although not completely new, the Sidescan sonar is worth being mentioned. The main work related to the integration of a Sidescan Sonar was previously conducted and is described in [6]. Another acoustic device, a multi-beam sonar was also integrated and is discussed in [4]. The mechanical and software integration was slightly changed to accommodate

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[1] http://tools.ietf.org/html/rfc2460

[2] http://tools.ietf.org/html/rfc793

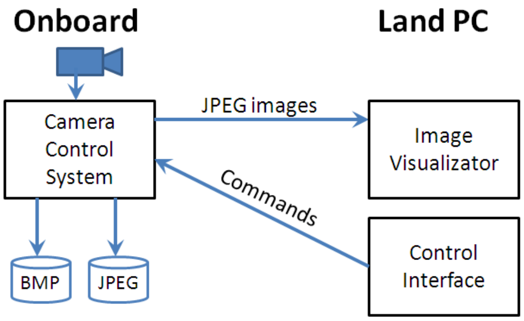

Fig. 3. Control system for the underwater camera

the presence of the underwater camera and the previously used mechanism to hold the StarFish 450F Side Scan Sonar was now used for holding the camera. A similar mechanical solution for the Sidescan Sonar was devised this time in the stern. A towed configuration was also tested in areas of greater depth. The idea of having both sonar and camera mounted at the same time is to fuse the images from the camera and the sonar imagery in a SLAM framework and this constitutes future work.

IV. IMPROVEMENTS OF USER INTERACTION

Relying on an advanced mission control and supervision system which allow a high level of interaction with the human user, suitable and ”easy-to-use” tools to enhance such interaction had to be integrated within the overall USV system framework. The new developed interaction tools developed for the Charlie USV system are: a custom reconfigurable multi-purpose console and an application executable on commercial Android-based smartphones [3]

A. *Console*

A new Console-based Human Computer Interface (CHCI) was developed to control the Charlie USV in order to help the human operator in performing fine maneuvering operations needed for instance to deploy the vehicle at sea, docking, taking the control of the robot in case of dangerous situations, etc. The CHCI, shown in Fig. 4, is designed to be a general purpose interface, in order to be easily adapted for maneuvering other robotic vehicles and it is composed of a water proof metal box with a high-luminosity sunlight readable monitor and a number of input devices (buttons, joysticks and knobs). The box is equipped with a Single Board Computer (SBC) with three PC/104-based boards and signal conditioning boards that are used to acquire the analog and digital I/O signals coming from the input devices. The input devices can be easily mapped by the user for setting the reference control variables. For example, in the case of the Charlie USV two main working modes are available: manual and semi-automatic. In manual mode it is possible to command thruster force and rudder angle with a joystick and a knob respectively. In semi-automatic mode, the same joystick and knob are used to set the reference speed and heading. A number of buttons are used for switching on/off thrusters, sensors (compass, sonar, etc.), light and horn, additional instrumentation. The CHCI software consists of two parts: one part manages the input devices and sends the related commands to the Charlie's control system while the second part receives the telemetry coming from the vehicle and shows it on the monitor. Various screen modes are selectable by the user and show different information. For example, one mode allows the user to monitor the status of the plant variables of the vehicle (e.g. thrusters faults, battery voltages, internal temperature, etc.); another mode shows the measures coming from the sensors (e.g. attitude sensors, GPS, altimeter, etc.), the command references and the video images acquired by an onboard above the surface camera. These images can be useful e.g. for obstacle avoidance and maneuvering.

Fig. 4. Console-based Human Computer Interface

B. *Smartphone*

An alternative Human-Computer Interface (HCI) running on a smartphone (SHCI) was also developed for the Charlie USV. The main idea in this case was trying to develop a HCI that would be on one hand less bulky and more portable than the CHCI and on the other hand that could exploit the new features present on the smartphones nowadays available on the market, in particular the touchscreen input capabilities and the attitude and inertial sensors. This SHCI can be used to substitute the CHCI in particular situations, for instance under logistic constraints (e.g. when piloting Charlie working from a small boat) and when a very complex control of the vehicle is not required. Due to the reduced capacities in terms of input and visualization furnished by a smartphone, the SHCI can only provide the user a subset of the control possibilities offered by the CHCI. The SHCI software was developed using Google's Android open-source platform and was run on a Samsung Galaxy S and an Acer Liquid Metal smartphones. At any rate each smartphone running Android OS providing a touchscreen and attitude sensors could be used as a compact, low-cost, low-power HCI for controlling marine robotic vehicles. The connection to Charlie's control system is an Ethernet channel obtained by means of the WI-FI interface present on the smartphone. The software was

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[3] http://www.android.com

developed using Google's Android open-source platform and was run on different smartphone devices, with the intent to be the as intuitive and ergonomic as possible and was targeted to be used not only by a professional user. Two main different application were developed, a first one allowing the user to control the vehicle in manual and semi-automatic modalities, relying on internal attitude sensor to set the desired rudder or heading angles and on-screen touchable items to command desired thrust force or speed. A second application, shown in Fig. 5, is instead based on the Google Maps service, showing the vehicle's position on the geo-referenced map, and also allowing the user, by touching the screen, to define a point of interest where the vehicle will start turning around. A preliminary test was performed in Genova Prà harbor and can be seen in http://www.youtube.com/watch?v=dkNkitdHQsc

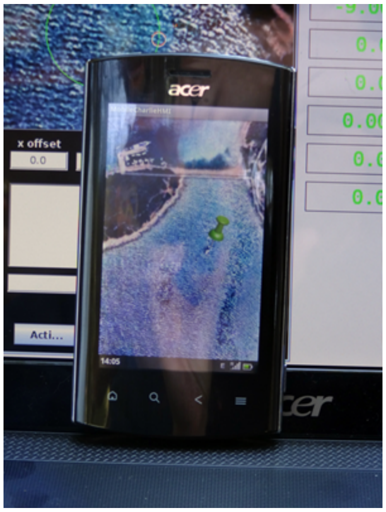

Fig. 5. Smartphone HCI at work

V. EXPERIMENTAL RESULTS

Experiments were carried out during a two weeks campaign in the framework, and with the support, of Breaking The Surface (BTS) 2011, the 3nd International Interdisciplinary Field Training of Marine Robotics and Applications hold in the Croatian island of Murter from September 19^{th} to 25^{th}, 2011, and organized by the University of Zagreb. The prototype USV involved in the trials was Charlie, a 2.40 m long, 1.70 m wide, autonomous catamaran, weighting about 300 Kg. The vessel, designed and developed by CNR-ISSIA Genova, is propelled by two DC thrusters with speed control guaranteed by suitable servo-actuators. The steering system is constituted by two rigidly connected rudders, positioned behind the propellers, and actuated by a brushless motor. The vessel navigation package is constituted by a GPS Ashtech GG24C integrated with a KVH Azimuth Gyrotrac, able to compute the True North given the measured Magnetic North and the GPS-supplied geographic coordinates. Electrical power supply is provided by four 12 V @ 40 Ah lead batteries integrated with four 32 W triple junction flexible solar panels.

A. Mission control

The mission control system was extensively used for long-track autonomous survey along lawn-mower grids, complemented by user-driven custom surveys, a result example is reported in Fig. 6. The exploitation of the mission control system was integrated with the novel user interaction devices, thus allowing non-technical users, in particular students and researchers with biological and archeological backgrounds, to operate the vehicle proving the concept of easy interaction with the user. A video of Charlie being controlled by means of a smartphone can be found in http://www.youtube.com/watch?v=kEbCzxXGVZw

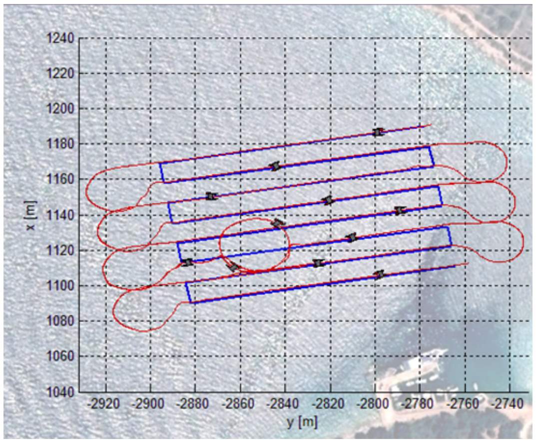

Fig. 6. Charlie USV automatic lawn-mowing manoeuvering: experimental results. Recorded path (red) vs. planned grid (blue).

B. Underwater camera

The main goal of these experiments was to collect data to be processed and analyzed and not to perform immediately the real time mosaicking. More than $75GB$ of video data were collected during the mission. Moreover, the work described in [13] will need to be improved to deal with some issues that did not arise while working with an ROV near the seabed. The change of illumination is one of the most important because it influences the contrast of the image and therefore the laser spots detection. The change in depth is another issue not only due to its influence in illumination but also for a matter of mosaic building and smoothness of the final result. Last but not least, although most of the tests occurred with good weather and sea conditions, part of the data was collected with some wind which implies the compensation of pitch and roll effects. Nonetheless, some preliminary results could be obtained and a partial mosaic is shown in figure 7.

C. Side scan sonar

As before, the StarFish 450F has a dedicated data acquisition and control system that runs on a SBC aboard the vehicle. In a similar way of the underwater camera, the data acquired through a USB port[4] is both logged on a local hard-

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[4] the proprietary USB communication protocol was made available to CNR-ISSIA by Blueprint Design Engineering Ltd. through a non-disclosure agreement

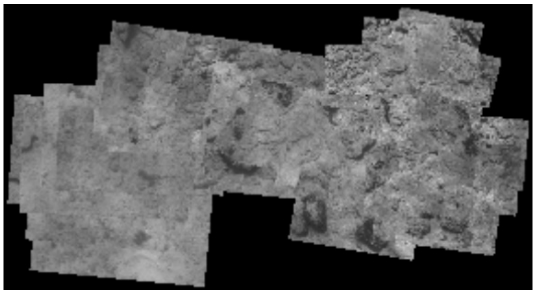

Fig. 7. Preliminary results on mosaicking

disk to further processing and sent to the remote station (after JPEG compression). The compression rate and the sampling rate can be tuned by the end-user through a simple GUI interface that also shows the composite image. Snapshots of sonar imagery acquired in the Roman city of Colentum are shown in figure 8. The Roman wall that was identified by the sonar could not be seen by the underwater camera as the water is too shallow on that area (less than 1 meter) making impossible to get video data.

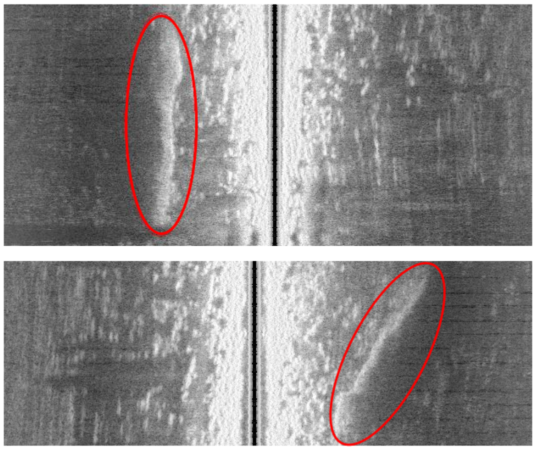

Fig. 8. Side Scan snapshots depicting a Roman wall in the ancient city of Colentum

VI. CONCLUSIONS

The mission control system proved to be reliable and more important well integrated with the new human-computer interfaces. Both the autonomous mode and user-driven modes allowed by the console and the smartphone were tested successfully. Several students and participants tested the HCI interfaces with no need of training whatsoever. The interface used to control the underwater camera proved to be very useful too both at the beginning of the mission and during the mission to adjust to the environmental conditions.

As future work, several aspects should be developed and improved. Namely, the above surface camera should be used not only for helping the end-user in teleoperation but also to automatic obstacle avoidance, shoreline mapping or other applications. In what concerns the sidescan sonar, a winch that can pull up or let down the sonar will help to adapt to the depth of the surveyed area when in a towed configuration. Moreover, this winch could be automatically controlled taking into account the depth measured by the echo-sounder. In the case of the resulting mosaic, geo-referencing it as in [16] is also desirable.

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