LOON-DOCK: AUV homing and docking for high-bandwidth data transmission

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Abstract— **Persistent deployment of underwater assets holds the key to achieve consistent, long-term undersea monitoring. To advance in that direction, the LOON-DOCK project aims to demonstrate remote AUV operation and survey data transmission through the Internet using an underwater docking station. We present a funnel-shaped docking station equipped with a contactless high bandwidth link and the necessary equipment to enable autonomous homing and docking by combining acoustic and optical sensing. The proposed combination, using a range-only localization at far distances and a light beacon localization at short ranges ensures a reliable strategy enabled with low-cost equipment and minimal requirements on both the vehicle and the dock sides. Moreover, remote operation is demonstrated by integrating the system in a unified web interface to control underwater assets, thus allowing a user to operate the AUV remotely through Internet. The full system has been successfully validated with tests conducted in a harbor environment.**

I. INTRODUCTION

The increased number of deployed subsea systems (infrastructures, sensors, vehicles) during the last years, suggests the need to interconnect them for a better management and exploitation, to monitor ocean processes and sustainably manage our planet. This is actually one of the major goals of the SUNRISE FP7 Project [1], which is devoted to make the Underwater Internet of Things a reality. Connecting the underwater systems to the network and endowing them with the capability of making their data widely accessible without the need of human interaction, has the potential of providing oceans data at an unprecedented scale. Although acoustics constitute the state-of-the-art in subsea communications, the provided bandwidth is a quantum leap far from the needs of transferring the gigabits of data usually gathered by an AUV in a single survey mission. The objective of the LOON-DOCK project is to extend the LOON (Litoral Ocean Observatory Network) testbed [2] with a docking station to demonstrate high-bandwidth data transmission from a survey-AUV to the Internet. The project is another step towards achieving persistent deployment of AUVs at sea, demonstrating how to remotely program a mission and download the gathered data through the Internet. The system has potential applications to the inspection and maintenance of submerged infrastructures like permanent observatories or subsea oil & gas field installations.

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Figure 1, illustrates the operational concept targeted by the LOON-DOCK project. Initially, the AUV remains in standby in the docking station. Next, a remote user connects to the system through the Internet by means of a web interface and schedules an experiment involving the AUV. The SUNRISE project has a web interface, named SUNRISE GATE [3], which is the one used for this purpose. Using the web frontend, the parameters for the desired survey are defined (waypoints, sensor-suite to be used for data acquisition, etc) and the experiment is launched remotely. The AUV undocks itself from the docking station and begins the survey. During its trajectory, data are generated (such as, multibeam sonar profiles, forward looking sonar images or optical imagery) and logged internally in the vehicle. Moreover, during the survey the remote user can monitor the operation, having the possibility to abort the mission and send the vehicle back to the docking station. When the AUV completes the survey, it docks back into the docking station. Finally, a TCP/IP connection is setup between the AUV and the external network through the contactless high bandwidth link, so the remote user can download the mapping data logged in the AUV to build the maps in his/her local computer.

The use of a docking station to extend deployment time has been explored since the 90's, starting from oceanographic applications [4], [5] and deriving later to more commercial scenarios [6], [7], [8]. Many options have been proposed with regards to the mechanical design of docking stations (including funnel-shaped receptacles [9], [10], [11] or vertical dock poles [5]) and their connectivity with the docking vehicle (with options involving direct mating [12], inductive coupling [13] or radio-frequency [10]). Also, different sensors have been employed for the homing maneouver, i.e., to guide the vehicle to the dock. Solutions include acoustic sensors (USBL [11], [10], inverted SBL [14]), optical sensors [9], [15], or electromagnetic ones [13], often combining acoustic methods for homing and optical sensors for the terminal guidance into the dock. However, despite numerous efforts and successful results, achieving persistent deployment of AUVs through a docking system is still an state-of-the-art problem [16].

Our approach consists on a funnel-shaped docking station that provides passive guidance of the AUV inside the dock, where a contact-less high-bandwidth data transmission system allows the AUV to transmit large amounts of mapping data to the top-side. The docking station is endowed with two systems to support the algorithms that allow the AUV to perform the homing and docking maneuvers autonomously.

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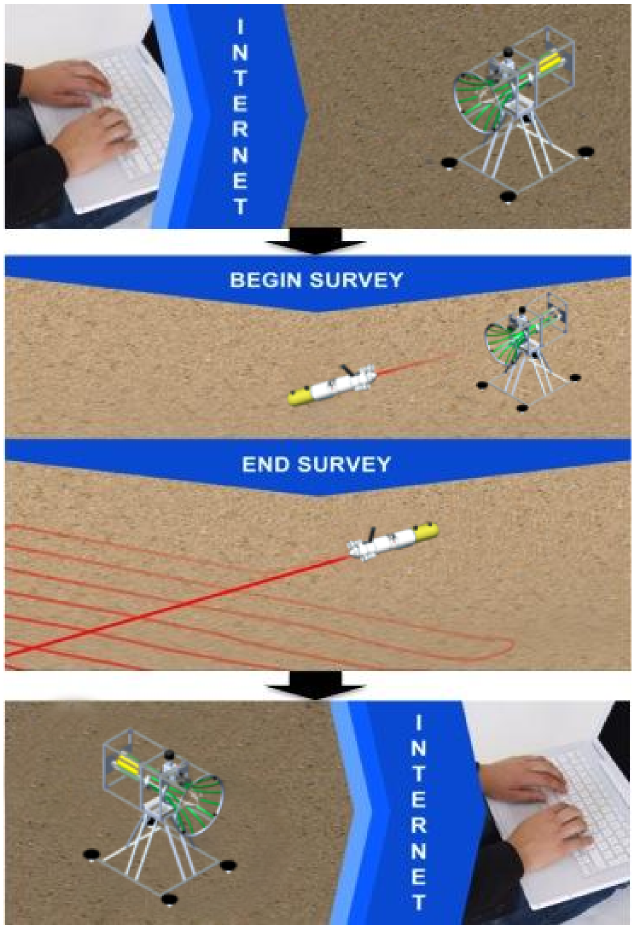

Fig. 1: LOON-DOCK project concept.

On one side, an acoustic modem that acts as a transponder for homing purposes. On the other side, a set of visual light beacons to allow visual-based position control during the final stage of the docking maneuver. An important aspect of this approach is the fact that acoustic ranging and optical image acquisition are capabilities that either already exist in most AUVs, or can be easily added at a reasonable cost. The same reasoning applies to the docking station, since the light beacon system is relatively inexpensive to manufacture. Battery recharging mechanisms, are left out of the scope of this work.

The rest of the paper is organized as follows: next section briefly describes the hardware involved in our system, namely the Sparus II AUV and the designed docking station. Section 3 covers the software developed for homing and docking as well as the integration with the SUNRISE GATE web interface to enable user remote operations. Section 4 reports the experiments performed in a harbour environment to assess the full system performance and last section summarizes the conclusions.

II. Hardware

To bring the LOON-DOCK concept to reality we have used Sparus II AUV [17] (see Fig. 2) a lightweight hovering vehicle with mission-specific payload area and efficient

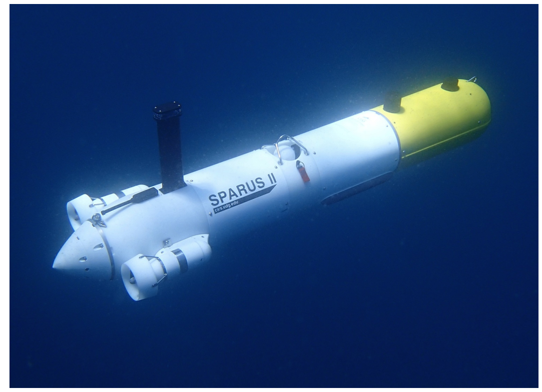

Fig. 2: Sparus II AUV.

hydrodynamics for long autonomy in shallow water (200 meters). Its flexibility, easy operation and openness makes the Sparus II AUV a multipurpose platform adaptable to a high variety of mapping applications. The docking station design (see Fig. 3) has been tailored to the Sparus II AUV, bearing in mind also to be small and lightweight. The main structure is composed of a funnel-shaped receptacle with 14 flexible rails that passively guide the vehicle to the dock position using vehicle's thrust. The docking receptacle is connected to a base that provides stabilization and levelling while allowing the top part to rotate and align with water currents.

A latching system has been developed to prevent the vehicle from exiting the docking station, thus allowing it to enter in low power mode once docked. For the AUV to transmit data to the top-side a WiFi modem has been adapted to fit in a waterproof housing and has been positioned on the latching mechanism. Thus, when the AUV is docked, its WiFi antenna is at a short distance from the modem ($\sim$ 7cm) which is enough to establish a strong wireless data link.

Finally, as mentioned before, the docking station is equipped with two active systems to provide localization information to the AUV and aid in the autonomous homing and docking maneuvers. An acoustic modem acts as a transponder providing long range measurements for homing purposes and also provides acoustic communications with the AUV for mission planning and on-line monitoring. For short range guidance, a set of four visual light beacons, each consisting of five high-intensity LEDs enclosed in a waterproof housing, are symmetrically placed around the entrance ring. The light beacons provide a flashing light at 1Hz period with 90%on- 10%off duty cycle.

III. Software

This section covers the software developed for the LOON-DOCK project. On one side we describe the modules implemented to achieve autonomous homing and docking maneouvers and on the other, the software to allow remote operation through the SUNRISE web interface.

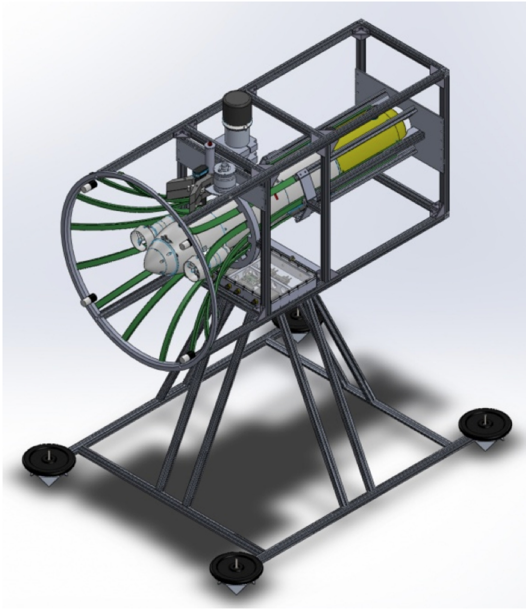

Fig. 3: Docking station design.

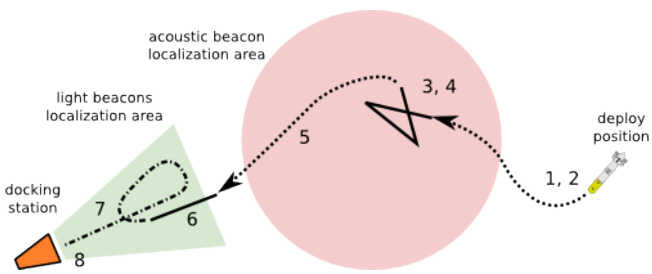

Fig. 4: Diagram showing the different steps in the autonomous homing and docking maneuvers. See text for details.

A. Software for autonomous docking

The implemented software to perform autonomous docking combines two complementary modalities. When the position of the docking station is unknown or known with a high uncertainty, a range-only localization method is used to obtain an approximate location. Once the vehicle homes to the vicinity of the docking station, the light beacon detection system provides more accurate pose updates. These pose updates are used to initialize a landmark in the EKF-SLAM navigation filter of the AUV. Once initialized, both range-only and visual-based updates can be applied. The details on the formulation of the filter can be found in [18]. Finally, once the vehicle is close to the detected docking station, a special high-level controller is in charge to conduct the terminal docking into the receptacle.

These different stages are conveniently combined by a state machine used for mission control. The main steps are summarized next (see Fig. 4):

1) A waypoint is created 40m in front of the *a priori* known docking station position.
2) The vehicle navigates towards the this waypoint.
3) The sum of Gaussians (SoG)filter is executed while following a star like trajectory to detect the docking station.
4) If a candidate position is detected, a waypoint is created 10m in front of it. Otherwise the state machine returns to step 1.
5) The vehicle navigates towards this waypoint.
6) The vehicle follows a trajectory towards the hypothetical docking station position while performing left and right turns. Once the light beacons are detected the docking station position is added to the EKF-SLAM filter. Otherwise, the state machine returns to step 4.
7) The terminal docking stage is executed.
8) If correctly docked, the latch mechanism to capture the AUV is activated. Otherwise, the undocking maneuver is performed and the state machine returns to step 4.

In the event that any of these phases does not succeed within three attempts the docking command is aborted and the vehicle is brought to surface. In the following sections we detail insights of the range-only and light beacon localization systems as well as the terminal docking maneuver.

1) Range-only localization: The range-only localization problem consists in determining the docking station position in a 3D space given 1D range measurements between the vehicle and the docking station beacon. To simplify the problem, we project the range measurements to a 2D scenario. For that we assume that the beacon depth is known *a priori*, since it is easy to be measured during the docking station deployment. Depth information provided by the AUV pressure sensors is also very precise, only having to take into account the tide, for which appropriate models are already available.

Thus, at known depth, a range measurement describes a beacon as being in any position on a circumference around the AUV with a radius equal to the projected range and thickness equal to the uncertainty of the measurement. To cover these big space of possibilities we use a SoG filter, which represents the static beacon positions as weighted Gaussians. The SOG is initialized with the first range measurement and the filtering is carried out in two main steps. First, the range measurement is used to update each of the Gaussians with an EKF. Second, the weights are updated with the innovation information. This procedure ensures that when following and observable path, the Gaussians that are not consistent with the observed ranges become negligible while those consistently compatible determine the estimated pose of the beacon. In order to avoid symmetries in the path and locate the beacon we use a star shaped trajectory. This trajectory is scaled proportionally to the first measured range and it is aborted as soon as the beacon is localized.

2) Light beacon localization: Using the on-board AUV camera, we detect the light beacons of the docking station in the camera images. This allows to estimate the relative pose of the AUV and the docking station with the full 6 degrees of freedom (3 relative translations and 3 rotations). The known blinking pattern of the light beacons allows to discern from potential reflections or shiny spots in the observed scene, therefore preventing wrong identifications.

The light localization algorithm is based on three main steps. First there is a selection of candidate spots in the image based on gradient information. Then, at every incoming frame, the candidates are tracked taking into account the camera motion and we check its agreement along time with the known blinking pattern. Finally, each candidate is associated with a beacon according to the known geometry of the beacons installed in the docking station. When four markers have been identified, the relative pose of the docking station that best fits the observation of the markers in the image is found using non-linear least squares minimization. An estimate of the pose uncertainty is also computed based on the fact that the uncertainty in locating a light in the image is inversely dependent on the distance between the beacon and the camera.

3) Terminal docking phase: After introducing the landmark in the EKF-SLAM , the terminal stage of the docking uses the estimated docking station position to compute the required control actions, therefore, it can be classified as a pose-based visual servoing. The aim is to guide the vehicle inside the docking receptacle using a line of sight (LOS) controller. However, it is possible that the alignment of the vehicle is not appropiate to face this final approach (e.g., due to water currents). Then, given the underactuated nature of the Sparus II in the sway degree of freedom, a series of movements might be required to place the robot to an appropiate position. This is done while maintaining, at the same time, the light beacons inside the field of view. Once in an appropiate position, a LOS with cross tracking error is executed to guide the AUV until the docking entrance and finally a force profile is applied to the thrusters to gently introduce the vehicle inside. In order to reinforce the visual localization during the very last few meters of the approach, when the four light beacons are not anymore inside the camera's field of view, a complementary system has been integrated using augmented reality markers [19]. Three known markers have been placed at known positions in the docking station and its relative position is estimated in an analogous way as done with the light beacons.

The verify that the vehicle is correctly docked, several tests are carried out. First, it is checked that the AUV position is static despite applying a small thrust. Second, the WiFi connection between the docking station antenna and the AUV is verified. Besides, a camera installed in the docking station pointing to the funnel provides visual feedback of the receptacle area.

B. Software for remote operation

The remote operation of the AUV has been demonstrated with the SUNRISE GATE web interface, which is the unified platform of the SUNRISE consortium from which to schedule experiments using different underwater assets around the world. In order to successfully transmit the commands that a user enters in the SUNRISE GATE web to the AUV and vice-versa (i.e., to transmit the mission to the AUV or the collected data to the user) there are several systems involved

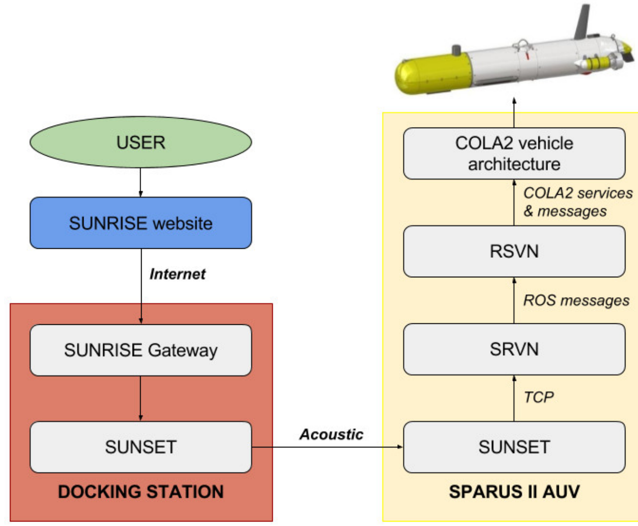

Fig. 5: Diagram of LOON-DOCK communications.

and a tight software integration had to be performed among them.

These communications have been handled with the use of the SUNSET networking framework [20], which is also developed within the SUNRISE consortium. SUNSET provides a set of commands that can be executed from the SUNRISE GATE and that can be transmitted acoustically from the docking station cabled node to the AUV node. Examples of these commands are orders such as abort, get the current position, set a plan including different maneuvers, start the plan, get a sample of one sensor, etc. Therefore, both the SUNSET framework and the GATE interface have been adapted to be able to handle new AUV-specific commands such as the ones to perform grid surveys or the dock and undock maneuvers.

Figure 5, shows all the blocks involved in the communication, from the user that access the GATE until the AUV. The user commands sent through Internet are translated to SUNSET commands in the control PC. These are then transmitted acoustically from the modem of the docking station to the modem of the AUV. However, because Sparus II AUV uses a ROS-based architecture, two additional nodes had to be implemented. The first, dubbed SRVN, is an interpreter that translates SUNSET commands to ROS messages and viceversa. The second, the RSVN, is a wrapper between the SRVN and the specific COLA2 architecture running in Sparus II AUV. It reads ROS messages and translates them into COLA2 messages or services.

IV. Experiments and Results

After validating the main algorithms in simulation [18], preliminary experiments using the built docking station have been performed both in a water tank (see Fig. 6) and in a harbour environment, proving the ability of the system to perform seamless autonomous docking and undocking maneuvers.

Initial tests in the water tank involved basic checks on the docking station hardware, experiments to test the light beacon localization system and the partial assessment of the mission control logic linked to the terminal phase of the docking maneuver.

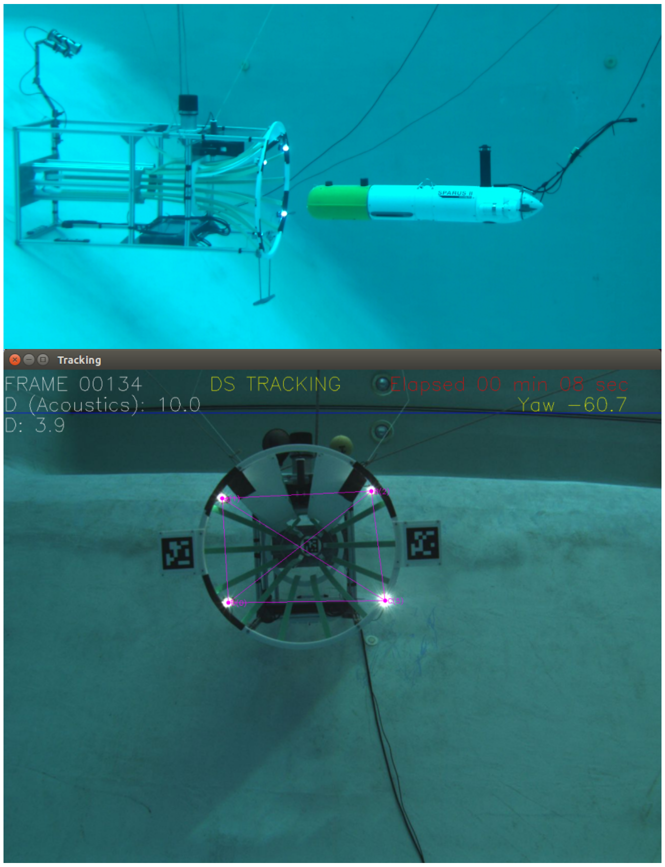

Fig. 6: LOON-DOCK preliminary experiments in water tank.

An extensive round of experiments has been also performed in a harbour environment seeking more realistic operational conditions. In this environment, without the space limitations of the water tank, we conducted tests to validate the AUV acoustic homing procedure to localize the docking station from far distances. Moreover, additional tests were carried out to check the light beacons localization as well as to validate the full mission controller of the docking maneuver.

Figure 8 shows the representation of the AUV trajectory during the homing phase in the harbour. The vehicle initiated the star pattern trajectory that is performed to increase the observability of the docking station ranges. The incoming range measurements quickly narrowed the probability of the docking station position to two possible locations, that were in agreement with all the received measurements. There were even some outlier range measurements (the smallest two circles that do not converge in the final determined position) but after performing the first two transects of the predefined star-shaped trajectory the approximate position of the docking station (red square) was determined with enough support to proceed to the light-beacon detection.

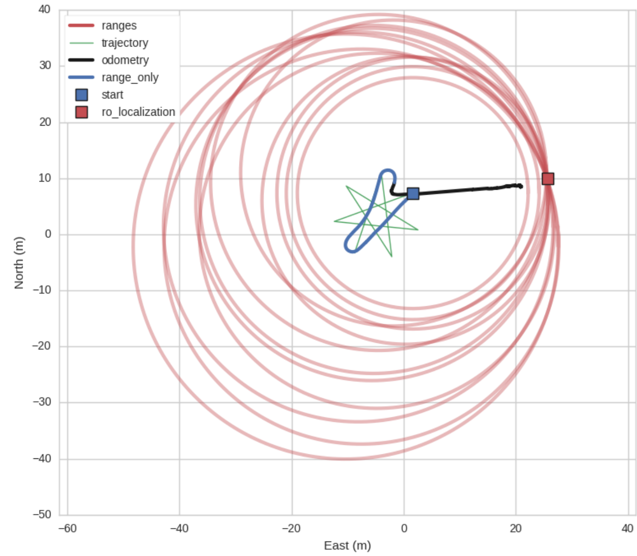

Fig. 7: Illustration of the acoustic localization algorithm executed in the harbour.

Regarding the stage of the light beacons, the algorithm demonstrated its capacity to localize the docking station, in real time, at 15FPS with a maximum delay of 0.1s, provided that the docking station is in the field of view of the camera and that all the lights are visible. The maximum distance of operation for the optical tracking depends strongly on the visibility conditions. In the harbour where tests took place the visibility was good and the light beacons could be properly detected up to 10m, enabling a good approach from afar. When the AUV is in the terminal docking stage following the LOS path it is difficult to keep 4 light beacons inside the camera's field of view for distances smaller than 3.5m. Then, the system relies upon the AR markers localization. Typically there is no need for updates under 3.5 to achieve docking (the vehicle will keep moving forward to the right position) but in situations involving water currents or DVL issues these updates can definitely help. Figure **??** shows an example of an approximation of the AUV to the docking station inside the harbor, where the visibility at different distances can be appreciated.

We have also verified that once docked and latched, the vehicle can transmit the survey gathered data through the WiFi module at speeds up to 45Mb/s.

Furthermore, the integration with the SUNRISE web interface, using the SUNSET protocol, has also been validated demonstrating the capability to operate Sparus II AUV remotely through Internet. First, experiments were conducted to assess the correct communication between the AUV and the docking station using the SUNSET networking framework. These tests had as a main objective to validate the proper functionality of the additional nodes that were implemented to handle the communication between the SUNSET and the COLA2 software architecture of Sparus II. Therefore, using the modems mounted in the docking station and the

AUV, we tested the correct transmission and interpretation of all the defined SUNSET commands. Especial emphasis was given to test the command that measures ranges between the docking station and the AUV, ensuring a proper functionality since it is key for the homing and docking maneuver. Finally, a SUNSET gateway was configured in the docking station control PC and an additional testbed was created in the SUNRISE GATE web to perform remote tests. Satisfactory experiments were carried out by sending commands to Sparus II AUV remotely from the SUNRISE GATE web (see Fig. 9).

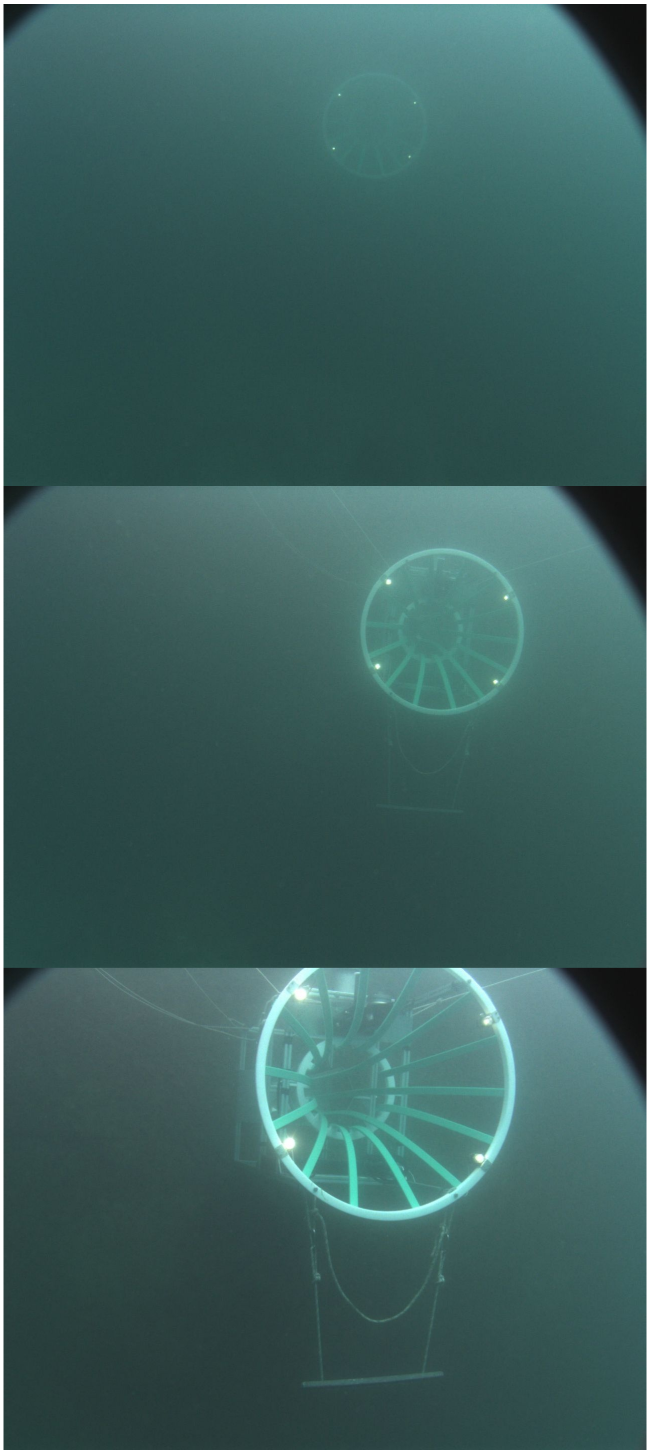

Fig. 8: Images of the light beacons in the harbour environment. Distances are approximately 7m, 4.5m and 2.5m.

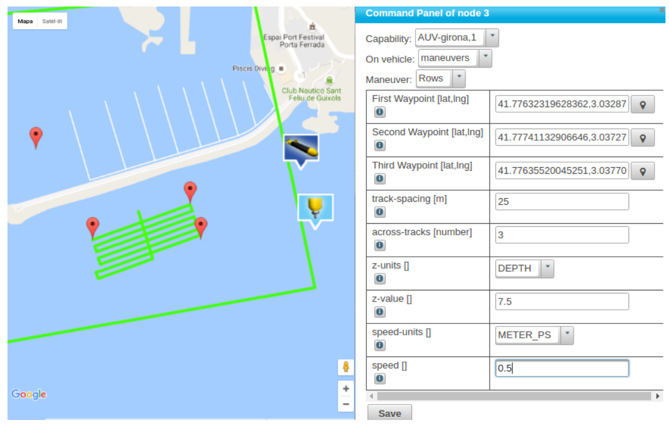

Fig. 9: Example of the definition of a grid survey through the SUNRISE web interface.

V. Conclusions

This paper has summarized the concept and advances performed in the context of the LOON-DOCK project, which is part of the SUNRISE FP7 project.

We have reported the implementation, both at hardware and software level, of a docking system, which is the key element that enables the persistent deployment and remote operation of an AUV in the LOON-DOCK project.

The docking station has been designed and built tailored to the Sparus II AUV, bearing in mind to be small, lightweight, and cost effective. It is endowed with a contactless high-bandwidth data link to send AUV data to the top-side and the necessary equipment to support the autonomous homing and docking maneuvers. The autonomous docking is achieved by combining a single beacon range-only localization algorithm at large distances, and a light beacon localization module over short distances. This combination allows the localization of the docking station from afar, while achieving enough accuracy to successfully perform the final docking maneuver. Tests conducted in a harbor environment testify to the good performance of the implemented methodology.

Besides, the full system has been integrated within the SUNRISE GATE web interface, using the SUNSET network protocol, with the aim to prove the concept end-to-end and demonstrate the remote operation of Sparus II AUV through Internet.

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