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Experimental testing of a cooperative ASV-ROV multi-agent system

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Abstract: The development of versatile and cost effective robotic tools for exploration and intervention in the underwater environment is presently a topic of interest in marine engineering. A viable, efficient solution is given by robotic platform that couple autonomous surface vehicles and unmanned underwater vehicles in integrated structures with various levels of cooperation. In this paper, we describe a number of field tests on the surface component of a robotic platform consisting of an autonomous surface vehicle that can automatically deploy and recover a small remotely operated vehicle. The aim of the tests are to assess the main functionality of the navigation, guidance and control system of the vehicle in relation to basic navigation tasks, both in supervised and in fully autonomous mode. In particular, in order to assure cooperation with the deployed remotely operated vehicle, the ability to track a target is considered.

Keywords: Autonomous Surface Vehicles, Navigation Guidance and Control, ROS Multi-Agent System.

1 INTRODUCTION

Monitoring and survey of environmental parameters, of marine structures and of underwater operations in coastal areas and shallow waters can greatly benefit from the use of robotic platforms that couple different robotic vehicles in integrated autonomous or semi-autonomous systems. Robotic structures that exploit cooperation and integration between Autonomous Surface Vehicles (ASV) and Unmanned Underwater Vehicles (UUV) at various levels have been proposed for, e.g., seabed surveys and data acquisition in Healey et al. (2002); Pascoal et al. (2000); Ferreira et al. (2011). In Djapic and Nad (2010), autonomous surface vehicles that can carry and deploy underwater vehicles in designated areas are considered for performing specific exploration or intervention tasks.

A robotic platform for scientific use that consists of an ASV equipped with an automatically deployable/recoverable small Remotely Operated Vehicle (micro-ROV) is currently under development at the Università Politecnica delle Marche. The platform, whose structure is depicted in Figure 1, is conceived to work in a partially supervised mode, in which the micro-ROV is remotely operated, through a radio link and the umbilical, from a shore-ground station and the ASV performs autonomously in order to guarantee the functionality of the integrated structure. The main advantages of such architecture is that it makes possible the deployment and the use of the micro-ROV avoiding the costs of a manned supply vessel. By exploiting two-ways transmission of data and commands through the radio link and the umbilical, the pilot of the micro-ROV can experiment telepresence in the underwater environment in an easy, economic way.

The main tasks which the ASV must be able to perform are autonomous navigation with the aid of navigation sensors (GPS, compass, and Inertial Measurement Unit or IMU) and formation keeping, with the aid of an USBL positioning system, with the micro-ROV, while the latter is freely guided by its pilot. The Navigation, Guidance and Control (NGC) system that takes care of those tasks and that governs all on-board apparatus for navigation, management of the micro-ROV, communication and power supply is organized as a Multi Agent System (MAS) in the ROS framework. Various steps in the development of the ASV component of the robotic platform have been described in Conte, De Capua and Scaradozzi (2012); Conte, De Capua and Scaradozzi (2015a); Conte, Scaradozzi, Sorbi, Panebianco and Mannocchi (2015b); Conte, Scaradozzi, Mannocchi, and Raspa (2016).

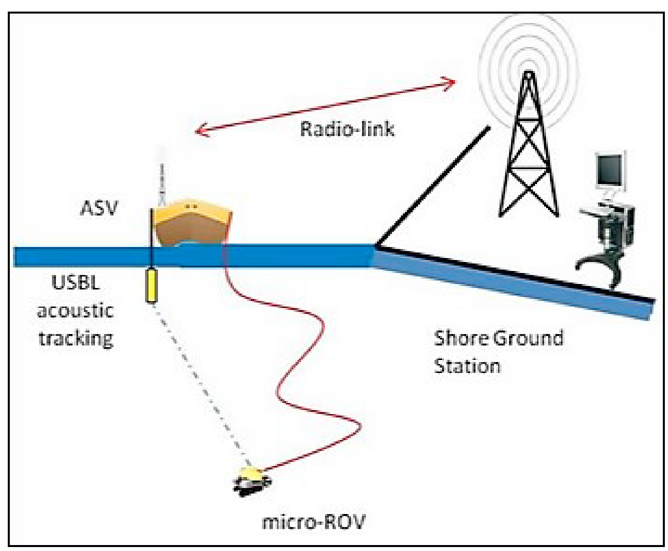

Fig. 1. The ASV/micro-ROV system

In this paper, we illustrate the results of a series of field tests that aim at analysing the functionality of the Navigation Guidance and Control (NGC) system of the ASV, both in supervised and autonomous navigation, and in evaluating the performances of a simple strategy in tracking a target that emulates the deployed micro-ROV. The paper is organized

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as follows. Section 2 summarizes the main characteristics of the mechatronic structure of the ASV and of the multi-agent system that governs it. Section 3 describes the experimental setting and it illustrates the results of the tests. Section 4 contains conclusions.

2 MECHATRONIC STRUCTURE OF THE ASV

The mechanical, hardware and software components of the ASV have been assembled using commercially available, low cost components-off-the- shelf (COTS). Differently from other vessels for scientific purposes, which are double-hull catamarans with two fixed thrusters, as those described in Ferreira et al. (2011); Encarnao et al. (2001); Miskovic et al. (2009); Melo and Matos, (2008), the considered ASV is a mono-hull boat with a unique steering, outboard electric motor. The mono-hull construction guarantees robustness and it facilitates transportation and deployment, while the use of a steering outboard motor increases easiness of installation, operation and maintenance. The aluminium hull is a Marine 10M boat (length 3,05m; max width 1,40m; weight 37Kg). The outboard electric motor is a Torqeedo Travel-503, equipped with a conventional nautical steering system: The steering system is actuated, by a stepper motor, endowed with an incremental shaft encoder. These components, or very similar ones, are available at reasonable price on the nautical market.

The mechatronic structure of the ASV is composed by a distributed set of subsystems, consisting of hardware and software components. The software components are organized as a multi-agent system (MAS) in the ROS framework, whose architecture has been described in details in Conte, Scaradozzi, Sorbi, Panebianco and Mannocchi (2015b); Conte, Scaradozzi, Mannocchi, and Raspa (2016). Agents take care of the subsystem's high level tasks and of the communication with other entities in the ROS framework in order to exchange data and to perform specific tasks in response to external inputs in a coordinate way.

Implementation of the ROS architecture on a distributed set of subsystem has been done by employing computing devices (Single Board Computer (SBC) and ARM Linux boards) coupled with micro-controller boards. In practice, the SBC and the ARM boards are used to execute the behavioural and decisional tasks that characterize the ROS agents at software level, while the micro-controller boards implement the control strategies that govern actuators and sensors at the hardware Level. The advantages of this architecture are the high computational capabilities to run decisional and ROS protocols provided by the ARM boards and the reliability of control performances assured by the use of dedicated microcontrollers. Details of the hardware architecture are given in Conte et al. (2015b).

The subsystem of the ASV structure that are fully operative at the present stage of development and that have been object of the tests are the following:

1. Central Control subsystem. It consists of a Single Board Computer (SBC) that hosts the ROS Master agent and other agents of the MAS. IMU, GPS and an IP-camera, with motorized pan and tilt mount, are directly connected to the SBC.
2. Engine subsystem. It consists of the outboard electric motor Torqeedo Travel-503 and of a custom board to implement the ROS agent that governs it.
3. Rudder subsystem. It consists of a mechanical steering system, which is actuated by a closed loop controlled stepper motor, and of an ARM Linux Board to implement the ROS agent that governs it.
4. Power subsystem. It consists of a gasoline-powered, portable electric generator and a battery, of a set of AC/DC and DC/DC converters and of a microcontroller to manage power.
5. On-Board Communication subsystem. It consists of wireless radio amplifier and a Wi-Fi antenna to communicate with the Remote Control subsystem and of an Ethernet communication infrastructure to connect all on board devices.
6. Remote Control subsystems. Located at a shore-ground station, it consists of a laptop, a wireless radio amplifier and a Wi-Fi antenna for communication. The laptop is endowed with a graphical user interface (GUI) to manage, to supervise and to monitor the vehicle and the other connected devices, like the micro-ROV and the USBL, and the ROS agents. The GUI is illustrated in Figure 2.

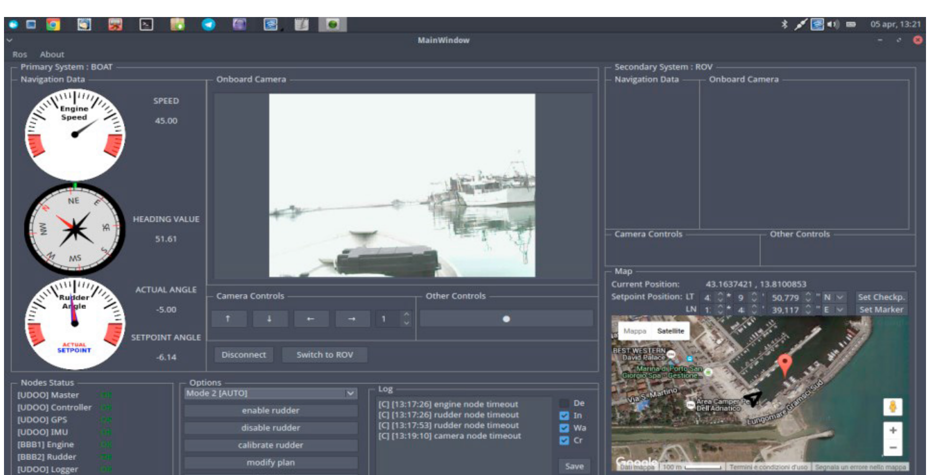

Fig. 2 GUI for remote control, supervision and monitoring.

Its main elements are the lower-right window showing the position of the ASV and, possibly of a target, on a Google-Earth map and the central window showing the IP-camera view. Current position in terrestrial coordinates is indicated above the lower-right window. On the left, three indicators show the (commanded and effective) thruster speed (in percentage with respect to the maximum speed), the heading and the rudder (commanded and effective) steering angle. The status of each ROS agent is shown in the lower-left window. Through the GUI, the pilot can guide the ASV (choosing between automatic or supervised mode), send commands (like position or speed references to the NGC system) and monitor the status and operations of the MAS.

The ROS agents that are currently implemented and have been involved in the field tests are the following.

1. Master agent. It coordinates the MAS in the ROS framework and it monitors the status of the infrastructure detecting and signalling failures.
2. Controller agent. It implements the NGC procedures of the ASV, as described below in Section 3.
3. Engine agent. It implements the open-loop control of the angular speed of the thruster of the outboard electric motor.
4. Rudder agent. It implements the control of the steering angle of the outboard electric motor.
5. GPS agent. It acquires and publishes, within the ROS infrastructure, the position of the vehicle obtained by the GPS.
6. IMU agent. It acquires and publishes, within the ROS infrastructure, attitude, rotational speeds and accelerations of the vehicle obtained by the IMU.
7. Camera agent. It streams video from the on-board IP-Camera and manages pan, tilt and focus according to external requests.
8. Logger agent. It logs the data published by the other agents to disk.
9. User agent. It implements the GUI of the system for remote monitoring and control.

3 EXPERIMENTAL RESULTS

The tests have been performed at the marine facility of Centro Nautico Mare & Corimac srl in Porto San Giorgio, Italy. During the tests, sea state and swell were 0 in the Douglas sea scale.

Figure 3 shows the ASV launching phase and the ASV in navigation. The micro-ROV VideoRay is visible on board. During navigation, one member of the team was on board to comply with safety regulation, which requires the presence of a crew to take control of the vehicle in emergency. A team of two members is enough to manage and to govern the system.

During the tests, data concerning navigation and status of the agent and the video stream generated by the IP-camera are transmitted to the shore-ground station and used to update the information on the GUI. Communication between the ASV and the shore-ground station is obtained by means of a 802.11 WiFi router, coupled with an amplifier and a high gain omnidirectional antenna (15dBi), on the boat and a directional high gain WiFi extender at the shore-ground station. Tests showed that during normal operation the network load remains below 20% of its capacity, thus guaranteeing that latency is almost negligible, as shown in Wheelis (1993) and Guosong et al. (2010). Maximum distance between the ASV and the shore-ground station was 300m and performances of the communication system in terms of average delay time, maximum delay time and package drop were in accordance with those measured in static conditions at a distance of 500m and reported in Conte, Scaradozzi, Mannocchi, Raspa, Panebianco (2016), respectively below 0,006s, 0,02s and 3%.

The system for deploy/recovery of the micro-ROV and the USBL positioning systems were not tested in this phase and the (projection onto the sea surface of) the micro-ROV's position was emulated during the tests about tracking.

Fig. 3. Launching the ASV and the ASV in navigation (crew is present only to comply with safety regulation). The shore-ground station is shown in the upper left corner.

The ASV operated for about 5h, performing several manoeuvres. During that time, collected data are
- position of the ASV in geographic coordinates;
- reference steering angle for the rudder (as commanded by the NGC system in autonomous mode or given as command in supervised mode);
- actual steering angle of the rudder;
- reference angular speed for the thruster (as commanded by the NGC system in autonomous mode or given as command in supervised mode) in percentage of the maximum speed;
- actual angular speed of the thruster;
- messages exchanged between the ROS agents;
- linear accelerations and angular velocities around the three IMU axis.

Power supply from the generator was voluntary cut off several times to test the capability of the power supply system to switch to battery mode and back when connection with the generator was re-established. All the on-board systems stayed active during cut-off, assuring full functionality, and no data were lost.

In the following subsections, examples of the general behaviour of the ASV are illustrated by showing trajectories on maps and by plotting: heading (hdng°); commanded thruster speed (cmd_thr_speed%); commanded rudder steering angle (cmd_rud_pos°); actual rudder steering angle (rud_pos°); average speed of the ASV (asv_speedkn), as computed by means of position data, together with: position of target (rov_latitude, rov_longitude) that emulates the (projection onto the sea surface of) the position of the micro-ROV; position of the ASV (ASV_latitude, ASV_longitude) and distance (distance) from the target during target tracking.

The steering system is mechanically limited by two limit switches and the maximum steering angle is 30° in both directions. The thruster angular speed is limited to 315 rpm (corresponding to 45% of its maximum value) in order to limit power consumption. The NGC system uses saturation limits of the rudder angle and thruster speed that take into account the thresholds given above.

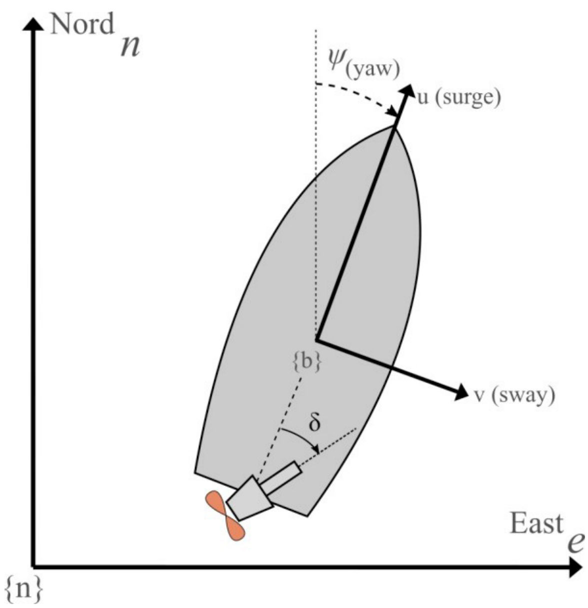

Fig. 4 Schematic representation of the ASV.

The IMU is fixed on-board in agreement with the reference system described in Figure 4, with the X axis pointing in the surge direction and the Y axis pointing in the sway direction and the Z axis pointing downward. The GPS module is set in DGPS mode using the WAAS (EGNOS) correction system.

3.1 Basic Motion

Basic guidance functionalities of the ASV have been tested during sea trials by using, first, basic motion commands. Each basic motion command consists of three values: the commanded thruster speed [%], the commanded rudder steering angle [°] and the command execution time [ms]. The command execution time specifies the time interval on which commanded values hold as reference. A sequence of basic commands forms a plan and the operator can specify or modify a plan and start its execution from the shore-ground station through the GUI. At the end of the overall time interval defined by a plan, the commanded variable are set to 0 by default. Data collected during these tests give first a qualitative evaluation of the response of the system and can then be used to identify its time constants and the values of physical parameters (e.g. drag coefficients, added mass, center of mass) as suggested in (Linder et al. ,2015) and in (Yoon and Rhee, 2003).

The circular path shown in Figure 5 is executed with a commanded rudder steering angle of 30° and a commanded thruster speed at 45%. As described in Fig. , after a transient in which the system reaches the steady state, the heading changes almost linearly, with negligible oscillations. Note that heading is represented without discontinuities when the using an extended scale for the angular measure.

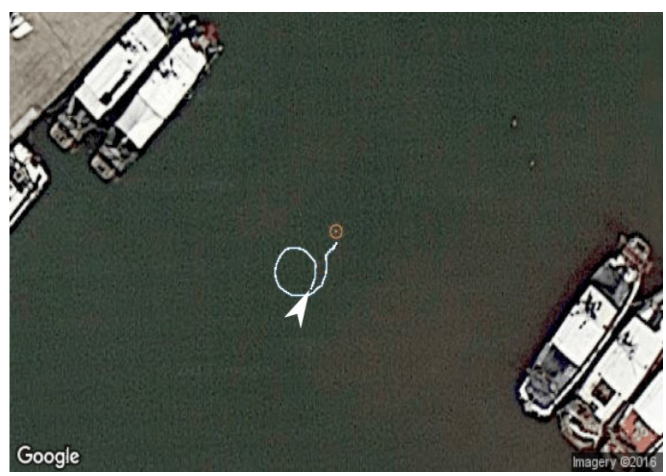

Fig. 5. Trajectory of the ASV during a circular path trial.

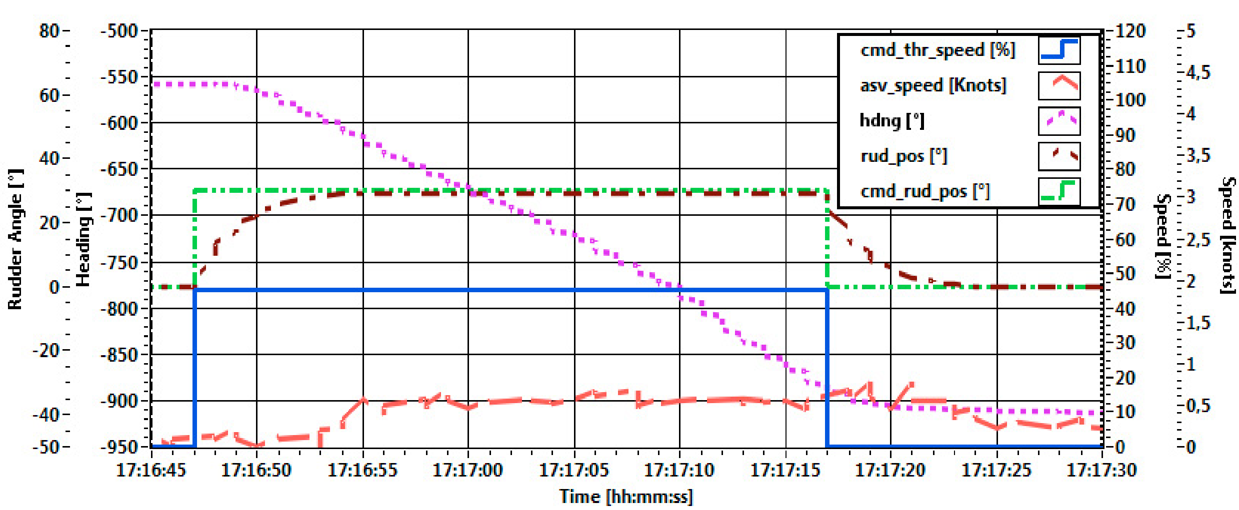

Fig. 6. Sensor data for the circular path of Figure 5.

The path shown in Figure 7 exhibits a zigzag pattern obtained by moving at constant speed and changing periodically the rudder steering angle. In the situation illustrated by Figure 8, the commanded rudder steering angle was sequentially set to 30°, 0°, -30° and 0° for, respectively 5s, 10s, 5s and 10s repeating two times the sequence, and the commander thruster speed was 30%. Data show the response of the rudder subsystem and of the ASV. Starting from 0°, the rudder steering angle reaches 90% of the saturation value 30° or -30° in about 5s and it returns to 0 in about 7,5s. In response to the motion of the rudder, the ASV heading exhibits a transient behavior that, commanding the steering angle from 0° to saturation for 5000ms and then again to 0°, terminates in about 20s.

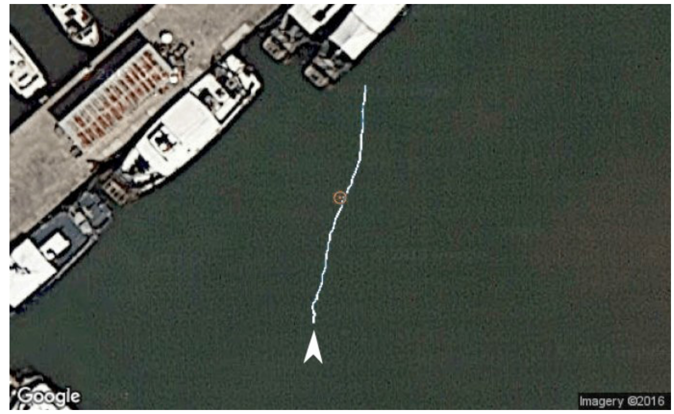

Fig. 7. Trajectory of the ASV during a zigzag path trial.

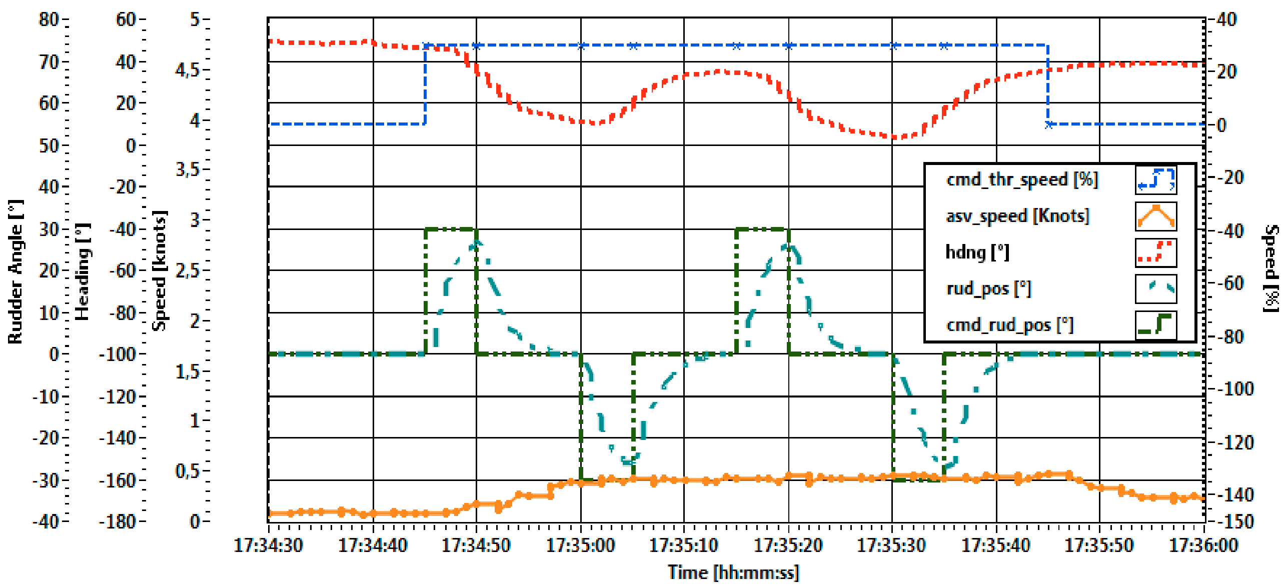

Fig. 8. Sensor data for the zigzag path of Figure 7.

3.2 *Target Tracking*

As mentioned in the Introduction, the main task the ASV has to perform is that of tracking a moving target. This ability is required in order to maintain below a threshold the distance between the ASV and the micro-ROV, when the latter moves underwater at a given depth. Practically, the ASV has to remain close to the vertical (projection onto the sea surface of the position) of the micro-ROV in order to facilitate management of the umbilical cable by minimizing its length and burden and to maximize precision in evaluating acoustically the position of the micro-ROV in survey and intervention tasks. Keeping into account the differences in the update rates of the position of the ASV and of the micro-ROV (GPS is faster than USBL) and velocities (the ASV is faster than the micro-ROV), the most natural way of behaving for the ASV is that of heading and moving toward the projection onto the sea surface of the micro-ROV position only if the relative distance is greater than a given value ρ and to rest if the relative distance is smaller than ρ. A discussion of this strategy and a possible implementation can be found in Conte, De Capua and Scaradozzi (2015a). In the present campaign of tests, such behaviour is obtained by adopting a Line-of-Sight guidance strategy that is implemented by the NGC system in two steps. First, the ASV heading is aligned, by moving the vessel along a circular path, along the loxodrome that joins its position with that of the target. Then, the ASV is moved in the surge direction at a speed that is proportional to the actual distance. Alignment and speed regulation are performed by applying simple, experimentally tuned, PID controllers. The distance ρ under which the ASV does not move is taken equal to 5m.

The thruster speed is computed taking into account also the rudder steering angle. In this way it is possible to limit the ASV speed during the alignment phase and to accelerate as the alignment error becomes small. The Line-of-Sight controller scheme is described in Figure 9. Tests were performed by forwarding at random times to the NGC system the GPS coordinates of a virtual target by means of a ROS agent. In future implementation, the ROS agent will get the GPS coordinates of the target directly from the USBL system which tracks the micro-ROV.

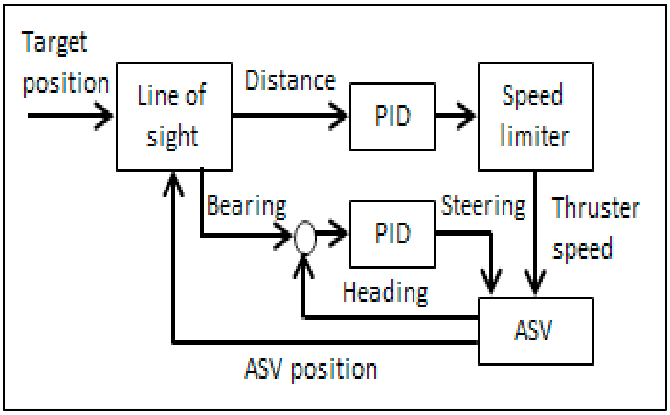

Fig. 9. Scheme of the Line-of-Sight controller.

Fig. 10. Trajectory of the ASV during tracking. Markers 1, 2, 3 indicate the position of the target at different times.

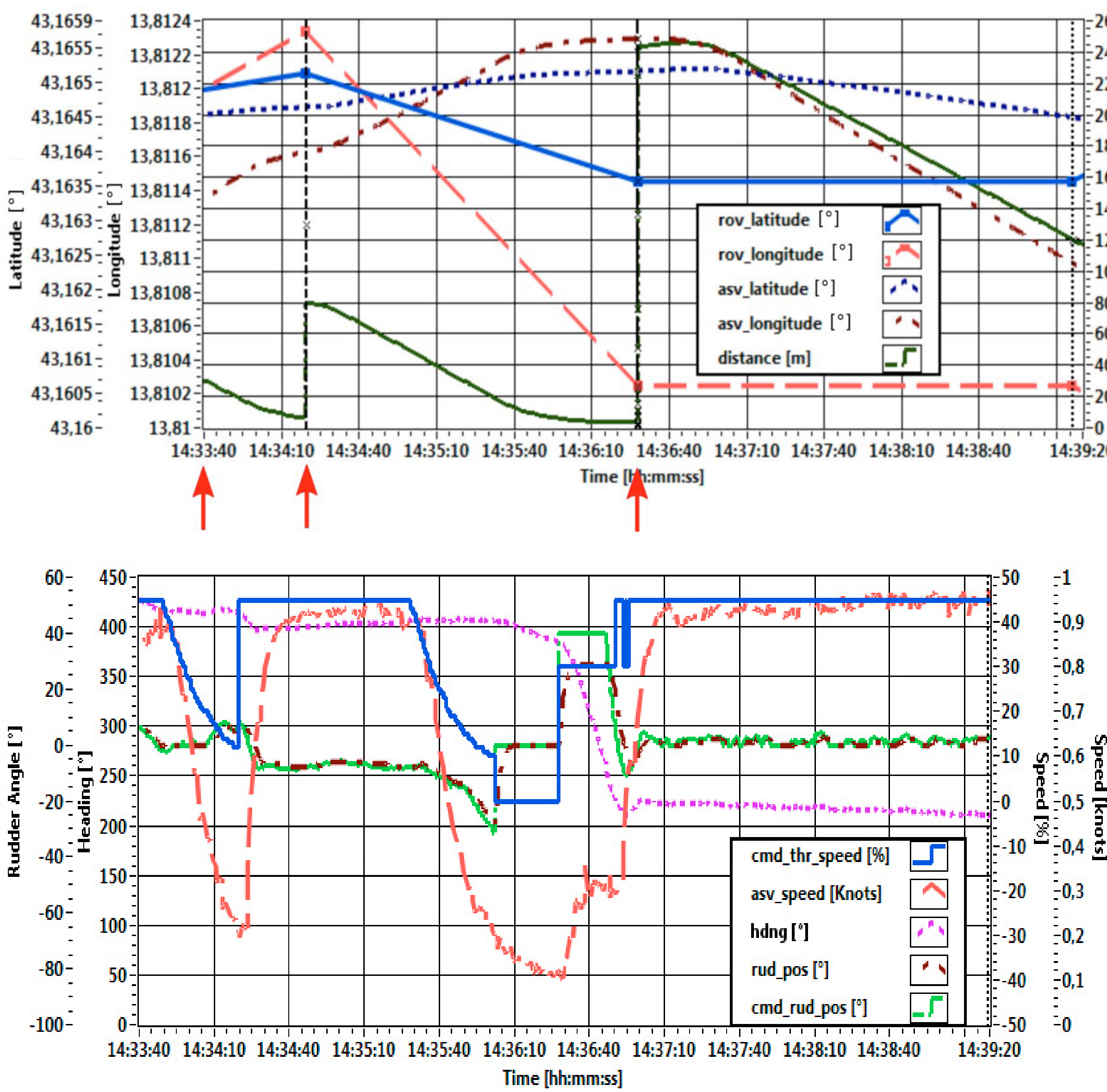

Fig. 11a); b). Sensor data for the situation described in Figure 10. Red arrows in Figure 11a) indicate the times at which position 1, 2, 3, respectively, of the virtual target are forwarded to the NGS system.

3.2.1 Tracking 1

Figure 10 refers to a worst-case situation in which, at a given time, the bearing of the ASV is opposite to the heading. The ASV, then, has to invert its heading in order to align it with the bearing. Markers 1, 2, 3 in the map mark subsequent positions of the virtual target, whose trajectory is outlined in yellow. The white trajectory of the ASV shows that it goes toward the target positioned in 1 and in 2 and then it inverts its direction to go toward position 3. Red arrows in Figure 11a) indicate the times at which position 1, 2, 3, respectively, of the virtual target are forwarded to the NGS system. Distance slightly increases while the ASV re-orients inverting its heading and then it start decreasing again. Time required for aligning the ASV in the worst-case situation is about 11s. The ASV stops when the distance from the virtual target becomes smaller than 5m and it reacts as soon as this condition is violated. Data collected can be used to tune the sliding mode controller that has been proposed in (Conte, De Capua and Scaradozzi, 2015a) to implement the tracking strategy.

3.2.2 Tracking 2

Figure 12 refers to another trial. Markers 1, 2, 3 in the map mark subsequent positions of the virtual target, whose trajectory is outlined in yellow. The white trajectory of the ASV shows that it goes toward the target and data are in accordance with those reported in Subsection 3.2.1 above. Collected data are shown in Figure 13.

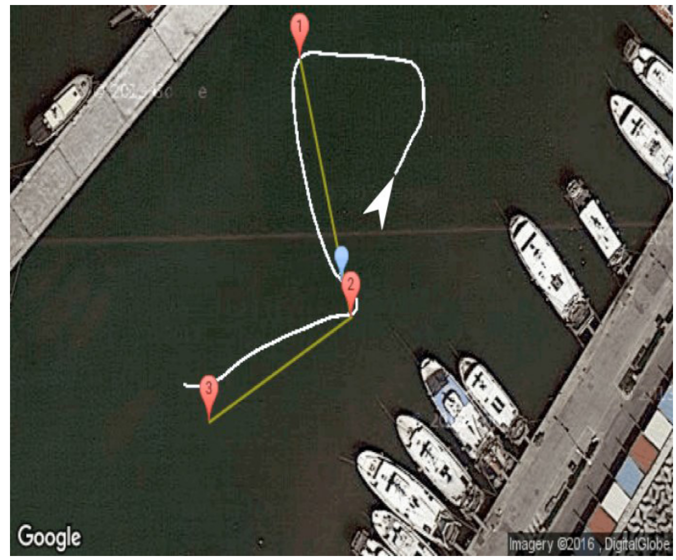

Fig. 12. Trajectory of the ASV during tracking. Markers 1, 2, 3 indicate the position of the target at different times.

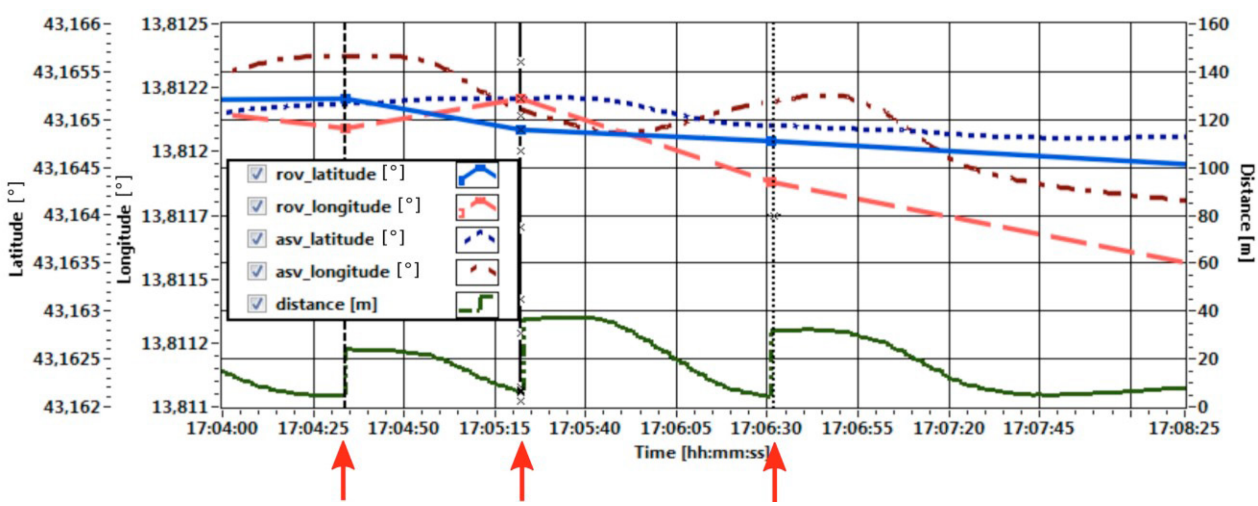

Fig. 13. Sensor data for the situation described in Figure 12. Red arrows in Figure indicate the times at which position 1, 2, 3, respectively, of the virtual target are forwarded to the NGS system.

4 CONCLUSIONS

The field tests performed on the ASV under construction have qualitatively shown operability and reliability of its mechatronic structure. Manoeuvring and tracking capabilities guarantee satisfactory performances in maintaining formation with the deployed micro-ROV. Future tests will experiment deployment/operation/recovery of the micro-ROV. Information about the position of the micro-ROV coming from the USBL system will be directly received by the dedicated ROS agent and then forwarded to the NGC system. The micro-ROV control console will be installed on-board and connected with the shore-ground station through the existing WiFi connection. Operator will guide the micro-ROV by means of position and visual information. Preliminary laboratory tests have already been done in order to assess performances of the network in transferring commands and video stream with positive results.

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