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Development of the Guidance Navigation and Control System of the Folaga AUV for Autonomous Acoustic Surveys in the WiMUST Project

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***Abstract*—This paper deals with the development of the Guidance Navigation and Control (GNC) system of the Autonomous Underwater Vehicle (AUV) used for acoustic surveys in the WiMUST projects. By exploiting the fact that the vehicle hull has a modular structure, a specific payload module was realized containing a single board computer, two acoustic modems, the electronic boards for signal conditioning and data storage of seismic data, and the mechanical interface for the streamer, the array of hydrophones that constitutes the main mission payload. Then, by using the Robot Operating System (ROS) the mission control system was implemented in the single board computer inside the additional payload segment. Motion control for the AUV was realized designing controllers for surge speed, heading and depth. Design of the depth controller represented one of the major challenges mainly because towing the streamer heavily affects the vehicle dynamics when underwater. Thus, a specific fuzzy-PID control system was implemented and tested. This one, together with the surge speed and the heading controller are discussed in this paper. Finally, selected experimental results from sea trials are discussed to prove the effectiveness of the presented GNC system.**

***Index Terms*—auv, depth control, surge control, heading control.**

I. INTRODUCTION

WiMUST is a project funded by the European Community within the H2020 framework, that started on February 2015 and ended in January 2018. The ultimate goal of the project was to design and test a system of cooperating Autonomous Underwater Vehicles (AUVs) able to perform innovative geotechnical surveying operations. In particular, the WiMUST system, is composed by a small fleet of AUVs carrying hydrophones to acquire sub-bottom profiling acoustic data. Contrary to the classical technology based on ship towed streamers, the WiMUST solution allowed a greater survey flexibility since the geometry, position and depth, of the acoustic antenna could be changed during the mission: something that had not been achieved in practice and represented a potential to significantly improve ocean surveying. The vehicles involved in the project were built by three different partners of the project: the Medusa AUV and the Delfim catamaran [1], [2], built by Istituto Superior Tecnico, the Folaga AUV built by Graal Tech Srl [3], and the Ulisse Catamaran, built by the Integrated System for the Marine Environment inter-university center (ISME), by the University of Genova ISME node in particular [4]. This paper is focused on the new Guidance, Navigation and Control system of the Folagas (a class of low-cost, light-weight autonomous torpedo-like AUVs) that was designed around the specific needs of the WiMUST project.

The rest of the paper is organized as follows. In Section II the AUV Folaga structure is described. The AUV Guidance, Navigation and Control system is formalized in Sections III and IV. Experimental results are discussed in Section V. Finally, the conclusions are presented in VI.

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II. FOLAGA AUV STRUCTURE

The Folagas are torpedo-like AUVs developed from Graal Tech Srl. The vehicle is actuated by 8 waterjet pumps and 1 propeller. The propeller provides trust along the surge direction, while the 8 pumps, 4 in the front and 4 at the rear, generate forces and torques on the vehicle that allow lateral and vertical translation, and pitch and yaw rotation; the roll degree of freedom is stabilized by changing the AUVs center of mass regulating the longitudinal position of the internal battery pack is mounted on a motorized frame. The Folaga AUV hull has a modular structure that allows adding one or more segments containing payload instrumentations. Within the WiMUST project, a specific payload module was realized containing a single board computer, two acoustic modems, the electronic boards for signal conditioning and data storage of seismic data and the mechanical interface for the streamer, the array of hydrophones that constitutes the main mission payload. The streamer, about 10 meters long and towed by the AUV, collects seismic signals reflected by the sea bottom in order to analyze its geophysical structure; Figure 1 shows 4 Folagas with their streamers laying on the dock.

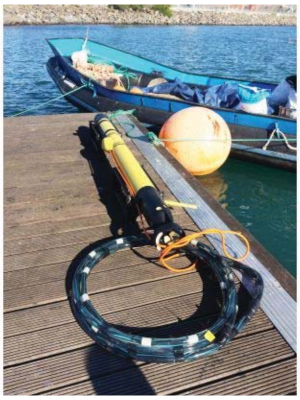


Fig. 1. The Folaga AUV with the streamer attached.

III. AUV CONTROL SYSTEM

The Folaga AUV has a built in mission control system that allows performing basic operations [5], [6]. Early tests in Lisbon and Sines (2016) highlighted that the existing Folaga mission control system could not be used for implementation of a complete WiMUST mission where precise trajectory tracking and coordination with other vehicles is necessary. Thus, a new mission control system was overlaid to the existing one in order to implement the necessary functionalities.

The new mission control system was then implemented in the single board computer inside the additional payload segment of the Folaga using the Robot Operating System (ROS), [7]. The use of ROS as middleware is motivated by the ease of integration with respect to the control modules that were developed by different partners.

Motion control for the AUV faces with three main challenges: surge speed, heading and depth controller. This section presents the implemented AUV control system. Detail on the navigation and guidance system will be described in Section IV.

A. Surge speed control

The surge speed controller was implemented as a PID controller. Given the surge speed tracking error $e_s = v_{ref} - v_{cur}$ (with v_{ref} the desired velocity and v_{cur} the current velocity of the vehicle), the control law is (in continuous time):

$$\frac{u_s(s)}{e_s(s)} = K_{Ps} + \frac{K_{Is}}{s} + K_{Ds}\frac{s}{1+s\tau_{hs}}, \tag{1}$$

where the pole in $-\frac{1}{\tau_{hs}}$ is needed both to make the derivative system causal and to damp the effect of noise. The current velocity v_{cur} must be estimated by the AUV navigation system. In order to actually implement the control law, a discretization of the continuous time controller transfer function was computed by using the forward Euler method with sampling frequency set to 10 Hz. Actually, an anti-windup technique was added to avoid, due to the presence of the integrator in the controller, that the error was continuously integrated also when the control input are saturated. However, in general, the reference v_{ref} is an input from an outer control loop system that generates velocity references with respect to the goal of the mission. Tuning of the controller was performed with extensive sea trials since the effect of the streamer drag was found to be very different along straight paths and in curves, and it was very difficult to predict reliably by simulation.

B. Heading control

The Heading controller was implemented as a PD controller. Given the heading angle tracking error $e_\psi = \psi_{ref} - \psi_{cur}$ (with ψ_{ref} the desired heading angle and ψ_{cur} the current heading angle of the vehicle), the continuous time control law is:

$$\frac{u_\psi(s)}{e_\psi(s)} = (K_{P\psi} + K_{D\psi}s)\frac{1}{1+s\tau_{h\psi}}. \tag{2}$$

where the term $\frac{1}{1+s\tau_{h\psi}}$ is needed to make the derivation system causal and to damp the effect of noise. The current heading ψ_{cur} must be estimated by the AUV navigation system and the reference ψ_{ref} is an input from an outer control loop system with respect to the goal of the mission. The actual control law running on the vehicle is obtained by discretization of the continuous time control law by using the forward Euler method with sampling frequency set to 10 Hz. The controller output produces a command that is mapped, through the control allocation technique, Section III-E, to the 4 horizontal pumps, hence producing a heading torque command. By considering the pumps if $u_\psi > 0$, then $|u_\psi|$ becomes the actuation command for front-left and rear-right pumps. Instead, if $u_\psi < 0$ $|u_\psi|$ becomes the actuation command for front-right and rear-left pumps. Tuning of the heading controller was performed with extensive sea trials as well; the presence of the streamer changed considerably the dynamics of the vehicle in turns since it generates a strong and time-varying disturbance torque on the yaw axis.

C. *Position hold*

The capability to hold the current position, although unusual for an AUV, revealed instead a fundamental feature for the WiMUST system, especially when initial deployment of all vehicles is performed. Even if the Folaga is fully actuated on the horizontal plane, and could be operated similarly to an ROV, in order to limit power consumption, the WiMUST Position Hold controller uses the underlying velocity and heading controller, and defines three different areas around the desired position: the maneuver zone, the hysteresis zone, and the hold zone, where different control strategies are activated resulting in a minimally energy consuming control system. In the maneuver zone, the vehicle turns toward the desired hold point and accelerates towards it. In the hysteresis zone, the vehicle keeps the behavior of the zone left just before entering it. In the hold ”safe” zone, the vehicle aligns with the desired heading and stops the propeller and all the pumps minimizing power consumption.

Figure 2 depicts the block diagram of the new Folaga mission control system developed for the WiMUST missions.

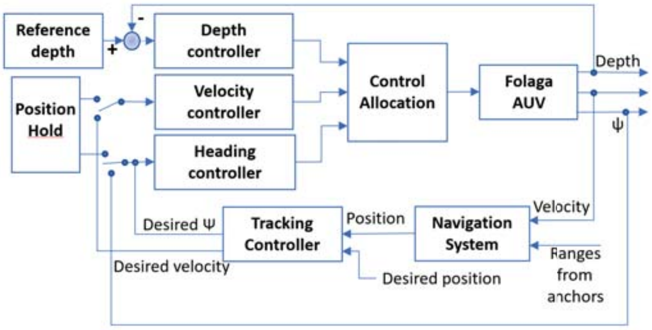


Fig. 2. Guidance, Navigation and Control system architecture.

D. *Depth control*

Design of the depth controller represented one of the major challenges, mainly because towing the streamer heavily affects the vehicle dynamics when underwater; in addition the velocity during the mission varies considerably due to formation changes and the effectiveness of vertical pumps changes greatly with vehicle velocity. Depth control on a vehicle like the Folaga may be implemented in two ways:

- using vertical thrust;
- using a pitch and dive approach.

Generating a vertical thrust using the vertical pumps to dive with an almost constant pitch angle and close to 0, is the only possible way when the vehicle is at zero velocity. This is the technique used by the Folaga AUV natively to change its depth when running water sampling missions for instance. This approach is less efficient, when the vehicle is cruising with a certain speed. This is due, mainly, to the loss of efficiency of vertical pumps when water is flowing along the vehicle body causing a loss of pressure in front of the water pump inlet. The second technique instead, exploits the vehicle surge speed to generate a vertical speed by pitching the vehicle. This approach is the most efficient since vertical speed, thus depth, is gained by simply tilting the vehicle. This technique cannot be used when the vehicle speed is close to 0. However, since the typical WiMUST mission requires changes of depth during the mission when the vehicles are cruising at a certain velocity underwater, this second technique was initially selected. It should be noticed that control system design and tuning becomes quite complex since it must take into consideration that vertical dynamics is a function of current horizontal velocity.

Depth control at low velocity is achieved with the vertical thrust approach: the necessary vertical thrust u_z is generated using a PD controller from depth error e_d:

$$\frac{u_z(s)}{e_d(s)} = (K_{Pzz} + K_{Dzz}s)\,\frac{1}{1+s\tau_{hzz}}. \tag{3}$$

The Pitch-to-dive depth controller is implemented instead using a cascade of two simple controllers: the outer loop controller computes depth tracking error and generates a desired pitch angle; the desired pitch angle becomes an input to the inner loop controller that regulates vehicle pitch to the desired value. More specifically, given the depth tracking error $e_d = d_{ref} - d_{cur}$ (with d_{ref} the desired depth and d_{cur} the current depth of the vehicle), a proportional control law was implemented, in continuous time, as:

$$\frac{\theta_{ref}(s)}{e_d(s)} = \frac{K_{Pd}}{1+s\tau_{hd}} \tag{4}$$

where the pole in $-\frac{1}{\tau_{hd}}$ is employed to limit noise transmission from the depth sensor and to generate a smooth pitch angle reference. The current depth d_{cur} must be estimated by the AUV navigation system and the reference d_{ref} is an input from an outer control loop system. Then the output of the first controller becomes an input for the second regulator that drives the pitch angle error toward 0. Hence, $e_\theta = \theta_{ref} - \theta_{cur}$ (with θ_{ref} the output of the outer loop depth controller and θ_{cur} the current pitch angle of the vehicle) and generates the command u_θ:

$$\frac{u_\theta(s)}{e_\theta(s)} = \left(K_{P\theta} + \frac{K_{I\theta}}{s} + K_{D\theta}s\right)\frac{1}{1+s\tau_{h\theta}}, \tag{5}$$

where the pole in $-\frac{1}{\tau_{h\theta}}$ is employed to make the derivative causal and to limit the effect of noise. Notice that the the pitch angle is measured through an inclinometer. As in the heading and surge control systems, a discretization was necessary to actually implement the controller. Hence, the forward Euler method with sampling frequency set to 10 Hz was used. The controller output produces a command that is mapped, through the control allocation technique, to the 4 vertical pumps, hence producing a pitch torque command.

However, there are missions or portions of a mission (e.g. the vehicle is turning in the inner part of the turn) where the velocity is low and the pitch-to-dive approach does not work efficiently. Thus, the Depth Controller was designed as a fuzzy-PID control system that blends the two, previously described, different control approaches: when the vehicle velocity is low, vertical pumps are used to control depth (with the vehicle almost leveled). When velocity is higher instead, the vehicle pitch angle is used as control variable to increase or decrease depth; this latter is the control mode that is used mostly throughout the mission. Figure 3 shows the conceptual block diagram of the so called pitch-to-dive and vertical-pumps-to-dive control systems mixed together with a fuzzy decision maker, based on the vehicle velocity.

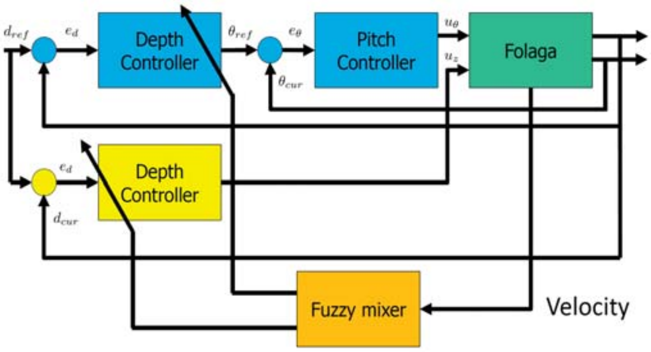
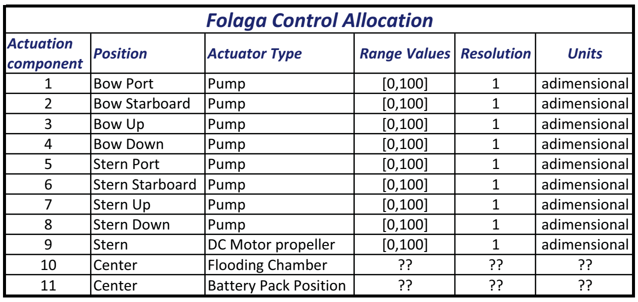


Fig. 3. Depth control scheme.

E. Control Allocation

The vehicle is actuated by 8 pumps, 4 mounted horizontally, and 4 mounted vertically. Pumps generate forces and moments on the vehicle by pumping water from the inlet to the outlet only and their direction cannot be reversed. The vehicle 8 pumps are mounted as 4 couples of opposite pushing pumps, 2 at the bow, and 2 at the stern. With this configuration, the 4 pumps command can be abstracted with an actuation system capable of generating forces and moments, that can take positive or negative values, along the Y and Z axis. Forces along the X axis can be generated using a propeller mounted at the stern. Moments around the X axis cannot be generated, nonetheless Roll stability of the vehicle is guaranteed by an accurate vehicle mechanical design. Pitch equilibrium point is obtained using a movable mass (actually the vehicle battery pack) inside the vehicle together with a flooding chamber that is able to change the vehicle buoyancy and make it neutral or floating on software command. Figure 4 presents the nomenclature and shows the pumps position on the vehicle.

IV. GUIDANCE AND NAVIGATION SYSTEM



Folaga Control Allocation

Actuation component	*Position*	*Actuator Type*	*Range Values*	*Resolution*	*Units*
1	Bow Port	Pump	[0,100]	1	adimensional
2	Bow Starboard	Pump	[0,100]	1	adimensional
3	Bow Up	Pump	[0,100]	1	adimensional
4	Bow Down	Pump	[0,100]	1	adimensional
5	Stern Port	Pump	[0,100]	1	adimensional
6	Stern Starboard	Pump	[0,100]	1	adimensional
7	Stern Up	Pump	[0,100]	1	adimensional
8	Stern Down	Pump	[0,100]	1	adimensional
9	Stern	DC Motor propeller	[0,100]	1	adimensional
10	Center	Flooding Chamber	??	??	??
11	Center	Battery Pack Position	??	??	??

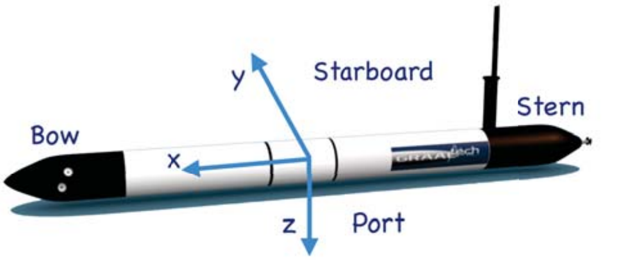


Fig. 4. The Folaga AUV reference frame.

The navigation system used when the vehicle is at the surface fuses vehicle odometry and GPS measurements using a Kalman Filter (KF). A different navigation system, developed by Istituo Superior Tecnico, Lisbn, one of the partners of the WiMUST project, is used when underwater. The underwater Navigation system is composed of a Kalman Filter and a Maximum Likelihood Estimator (MLE). These two, together, use measurements of ranges between the vehicle and a set of anchors to estimate the vehicle position when underwater. The anchors are equipped with acoustic modems that ping periodically sending current anchor position and time. Ping times are synchronized using the GPS Pulse-Per-Second (PPS) signal; estimation of distance is performed by measuring the time of flight of acoustic signals and using Chip-scale Atomic Clocks (CSAC) inside the modems allows keeping a common time base with minimal drifts during the entire duration of the mission. The vehicles after reception of the pings from the anchors, calculate their distance from them, and use this information to update the position estimate in the Kalman filter. At least two anchors are needed to compute a position fix; in the WiMUST architecture, surface vehicles (the two catamarans usually) act as anchors. Thanks to the adoption of ROS as middleware, the KF and MLE components were implemented as two ROS nodes that run unmodified on the Folagas and the Medusas, even if the two AUVs differ both in hardware and software. The MLE node requires an estimate of vehicle velocity as input; since no DVL is present on the Folagas, a static mapping between propeller RPMs and vehicle velocity was created through extensive tests performed in La Spezia (Italy). Also in this case, the presence of the streamer represented a major issue in determining a reliable RPM-Speed map. The Guidance system is implemented by the Tracking Controller ROS node, developed by IST and University of Hertfordshire (UH). The Tracking Controller computes feasible reference velocity and heading angle for the AUVs and the catamarans in order to guide the vehicles from their initial positions toward the mission starting point prior to the start of the survey, and to remain in a fixed relative position with respect to the formation leader during the survey. In addition, an observer [8], is employed to estimate sea current in order to achieve a very precise formation tracking. Sea trials in La Spezia, Lisbon and Sines were performed to field test the integration and to assess the Folaga vehicle capability to remain in formation while underwater.

V. EXPERIMENTAL RESULTS

This Section presents selected experimental results from sea trials in La Spezia, Lisbon and Sines that, starting in early 2016, culminated in the final seismic survey experiment in January 2018. In order to prove the effectiveness of the proposed control system for the Folaga AUV, several results from different sea trails conducted during the project are presented.

A. Surge speed control

Figure 5 shows a comparison of actual and desired surge speed and the percentage of thruster command u_s.

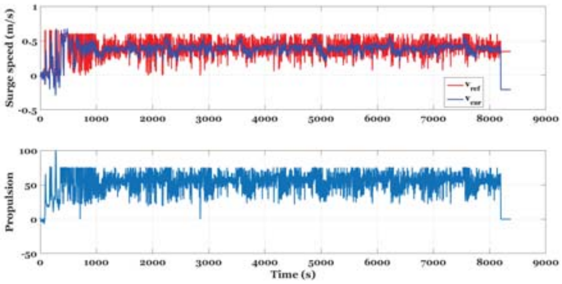


Fig. 5. Surge speed control in the final survey in Sines, Portugal.

B. Heading control

Figure 6 shows a comparison of actual and desired heading angle and the lateral command u_ψ converted from control allocation into lateral water jet pumps commands. The front and rear pumps are used in differential mode. Front left and rear right work together with the same percentage value; the same is true for front right and rear left pumps.

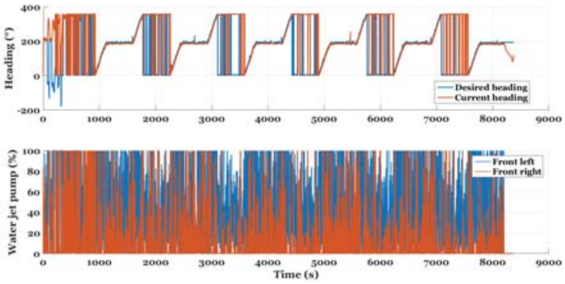


Fig. 6. Heading control in the final survey in Sines, Portugal.

C. Position hold

Figure 7 shows relevant variables for the position hold control system. The vehicle entire trajectory, and a zoom around the position hold point are shown on top of the Figure; the bottom part shows a comparison of actual and desired speed and heading angle. In particular, it can be noticed that the desired surge speed has three possible levels: the desired speed is set to 0 m/s when the AUV is inside the hold zone; if the AUV is inside the maneuver zone, the desired surge speed is set instead as a function of the heading error e_ψ. If the heading error is greater than a threshold, the desired surge speed is set to 0.1 m/s, otherwise is set to 0.4 m/s. The desired heading is set at the constant desired value when the AUV is inside the hold zone and hysteresis zone. This value is set by mission control and is usually meant to facilitate the successive entrance into formation. When the AUV is inside the maneuver zone instead, the desired heading is set to orient the vehicle to bring it back to the waypoint, using the so called Line-of-sight guidance.

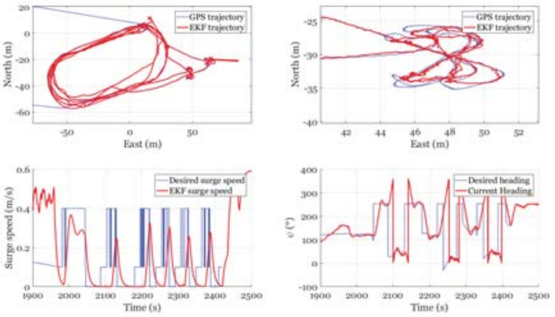


Fig. 7. Position hold during sea trials in La Spezia (Italy).

D. Depth control

Figure 8 shows vehicle actual depth with respect to commanded depth (7 meters in this experiment), and the actual pitch angle θ with respect to commanded pitch angle θ_{ref}. It can be noticed that the initial dive from the surface to 7 meters depth is achieved by pitching the vehicle nose-down of about 10 degrees; when the desired depth is achieved, the commanded pitch angle remains closer to 0.

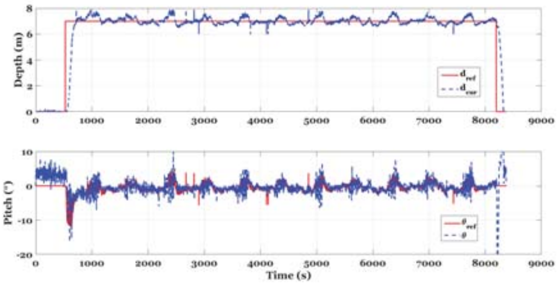


Fig. 8. Depth and Pitch control in the final survey in Sines, Portugal.

Figure 9 shows the operation of the Fuzzy mixer; only a brief portion of the mission is shown for cleanness: when, around t=4900 sec the vehicle starts turning to follow the formation, it slows down since it is positioned at the right of the formation leader (that is turning to the right); this can be seen from the fuzzy scheduling variable α which value varies between 1 (when speed is large enough and only the pitch-to-dive controller should be used) and 0 (when only the vertical-thrust-to-dive controller should be used). When the vehicle speed is lower, the depth controller with the pitch-to-dive method is less effective and the vertical-thrust-to-dive controller starts operating; also shown are the outputs of the two depth controllers u_θ and u_z. When the Fuzzy mixer starts operating, the control action is the result of the mixture of the vertical-trust-to-dive and pitch-to-dive controllers actions; thus the 4 vertical pumps are used both differentially to generate a pitch moment, and with same direction to generate the needed vertical thrust.

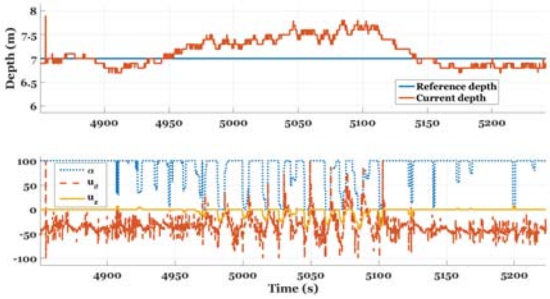


Fig. 9. Sample

E. Full Mission

Figure 10 shows a comparison of the GPS trajectory and acoustic estimated underwater trajectory. At beginner of surface mission the trajectories GPS and acoustic are equal. When the Folaga AUV go underwater the GPS trajectory jump, because GPS signal cannot be received underwater. During the underwater mission, the AUV utilizes the acoustic communication to localize itself. At the end of the mission the AUV come back on surface. Finally, Figure 11 shows the underwater position in UTM coordinates of Folaga AUV and acoustic ranges from Folaga AUV to surface anchors.

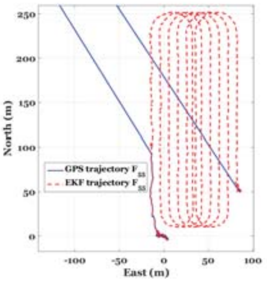


Fig. 10. Trajectory underwaterin the final survey in Sines, Portugal.

VI. Conclusions

This paper has presented the structure of the Folaga Guidance Navigation and Control System designed around the peculiar needs and challenges of the WiMUST EU funded project. Details on the surge speed, heading, position keeping and depth controllers were provided together with results from the several experimental campaigns that were conducted during the three-years project, including the final demo In Sines, Portugal, January 2018.

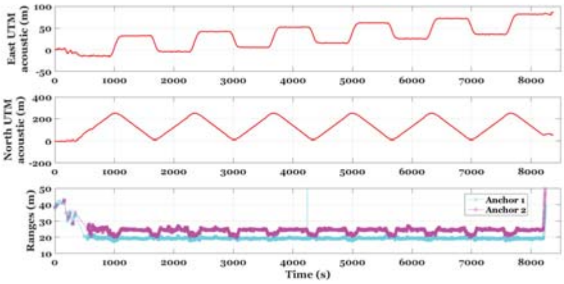


Fig. 11. Acoustic position and ranges in the final survey in Sines, Portugal.

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