Design and control of an Autonomous Surface Vehicle to improve Link Communications

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1. INTRODUCTION

Seas and oceans cover 71% of the surface of the Earth's crust. This huge extension, enormously unknown due to the inherent difficulties to carry out its exploration, provides a challenge to scientists who try to discover the secrets they hide. Some of the difficulties encountered fall into the complexity of maintaining underwater communications. Classical air communication systems such as Wi-Fi or radio frequency lose their full functionality a few inches below the water. On the other hand, the sound is transmitted at about 1500m/s to the sea water providing the possibility to establish communications at great distances in a satisfactory way.

The most common solution to establish this kind of powerful submarine communications is the acoustic modem. A more sophisticated modem variant is known as Ultra Short Base Line (USBL). Thanks to the geometric layout of several receivers at one end of the acoustic link, this device allows to measure the position of the remote emitter. Therefore, USBL acts as a submarine communication system and at the same time provides the relative position between the transmitter and the receiver. Generally, the positioning unit is located at a point close to the surface, either fixed to the coast or on a ship, while the simple transmitter receives on board the autonomous submarine vehicle. In this way the positions of the submarine can be referenced while executing a mission.

Using the USBL by entering it and fixing it in shallow waters, either on the sidewalk or from a boat implies a series of problems in avoiding the shadows produced by the boat hull or by the possible reefs located between the emitter and the acoustic receiver. In addition, the possible reflections of the acoustic waves generated by bounces, both at the bottom and on the surface of the water also difficult the communications. In order to avoid these problems, the construction of an autonomous surface vehicle (ASV) has been proposed with two basic functionalities. First of all, the ASV will be in charge of maintaining a position close to the vertical where the submarine vehicle is, in order to minimize the separation between the transmitter and the receiver and in this way reduce the probability of bounces or collisions of the acoustic waves that travel between one and the other. On the other hand, the ASV will be equipped with a radiofrequency link in order to maintain broadband communication with the base station on board a boat or on the coast.

1.1 Background

The use of autonomous underwater vehicles for mapping, manipulation or maintenance has increased in the last fifteen years. This kind of vehicles have also become a powerful scientific research tool in ocean exploration. The *Systems, Robotics and Vision* (SRV) research group linked to the University of Balearic Islands, has developed and operated several Autonomous Underwater Vehicles (AUVs) and Remote Operated Vehicles (ROVs): e.g. *Fugu* mini ROV (self made) (Bonin-Font et al., 2015), *SeaLion* ROV from JV Fishers, and Turbot, a SPARUS II AUV (Carreras et al., 2013). (Martorell-Torres et al., 2018) All these platforms have shown a common drawback, when they are operated in AUV mode: the communication link to the operator.

Nowadays the main activity of the SRV group is focused on Turbot AUV. This robot is equipped with different sensors including an acoustic modem which allows the acoustic communication link (ACL). The main functions of the Turbot AUV are the video recording of the bottom of the sea to perform mosaics or 3D reconstructions. The missions that they usually do are characterized by shallow water, untethered navigation and covering an area under 700 m^2.

Underwater robotic platforms can either be (i) tethered, e.g. connected to the operator through cable means, which limits operability, range and adds complexity in forms of cable management systems, cable tension and buoyancy compensation, and many more; or (ii) untethered. In this second scenario, if the vehicle should keep the ability to communicate or receive orders while underwater, acoustic communications are the most used solution, alongside with short-range radio (Palmeiro et al., 2011) or even optics (Cox et al., 2011).

Underwater communications are very limited. Radio frequency technology, which is widely used in the air, is not acceptable underwater for a long range link due to strong absorption. Thus, most effective systems are based on acoustics. USBL systems are a common solution because, using an array of hydropones, they can achieve communication and positioning of the rover unit. Usually, an USBL transducer array is rigidly fixed to a support vessel or to a mooring buoy. These kind of configurations tend to increase sound perturbations. In the first case, perturbations caused by ship propellers and hull vibration affect the positioning and acoustic link. In the second case, seafloor and surface are close enough to cause multi-path echoes and reflections before reaching the target (Hyakudome et al., 2016).

To overcome some of these issues, facilitate the ACL deployment and increase the operation area, we propose to carry the USBL on an ASV that closely follows an AUV to improve signal quality and reduce multi-path. Moreover, operation costs are also reduced since no support vessel is needed.

This work has the objective of design and control remotely or autonomously a surface vehicle that links to an AUV and the scientists that are in charge of manage and control the activity of the underwater robot. In addition to performing this function to facilitate communications, it must also be easily configurable in order to be able to provide different services such as bathymetries, collect water samples or other possible future operations.

The vehicle set requirements are: have enough buoyancy to carry all hardware components and maintain a free gap to allow to increase the payload weight. Choose the right commercial thrusters in order to obtain the needed thrust to ensure an effective navigation. Create a rigid and stable frame which ensures the stiffness of the aluminum extruded profiles structure. Guarantee enough power source to allow the navigation during the AUV missions. Finally, create a software architecture that implements the functions to maintain and improve the communication link between the AUV and the base station.

The platform can be operated in the following ways: (i) Autonomous Underwater Vehicle (AUV) tracking, where the vehicle is required to track a moving frame (e.g. the AUV) without the need to know the actual position of the platform, (ii) path following, where the objective of the vehicle is to achieve a number of waypoints in a time window and (iii) station keeping, where the vehicle holds its GPS position regardless of the wind or water currents. Moreover the vehicle should have the ability to navigate remotely through a (iiii) teleoperation mode.

1.2 Related work

Autonomous surface vehicles proven to be a very important tool to operate in the gap were other systems like AUVs are not suited to operate. Tracking AUVs from ASVs has also been explored in (Braginsky et al., 2016), where a kayak loaded with acoustic communications and thrusters is used as ASV to track an AUV. The authors used a ranger system to follow the position of the AUV with $\pm 2\ m$ accuracy.

Tracking an underwater acoustic source can be performed in several ways, such as tracking from a surface vehicle, an underwater vehicle or from an underwater sensor network (Majid and Arshad, 2016b). Among these methods, tracking from an ASV is the most flexible in terms of simplicity, easy to monitor and cheaper operation (Majid and Arshad, 2016a). ASV also reduces the operational costs and overcome many of the limitations involved with a sole AUV (Thirunavukkarasu et al., 2017).

In (Daxiong et al., 2013),a tracking control method of ASV following AUV using acoustic sources is developed. Daxiong describes an acoustic communication system to predict the ASV position and adjust the speed according to the AUV distance.

The design of a low cost autonomous surface platform was explained in (Curcio et al., 2005) where the engineers of the MIT Department of Ocean Engineering designed a vehicle based on a kayak frame. The objective of this vehicle was to create an inexpensive platform in order to provide a suitable source for development and mission planning. The sensors used to navigate were GPS and compass, furthermore a long baseline navigation system and omni directional radio frequency antenna were used to link communications.

Finally, it is important to highlight the work of (Ferreira et al., 2007) where an ASV with catamaran structure was developed with the main objective to act as a center operation network between an AUV.

The paper is structured as follows: the section 2 shows the design of the ASV, section 3 explains the hardware components used, section 4 covers the software architecture implemented, in section 5 the navigation behaviours are detailed, in section 6 results from framework tests are presented, in 7 the economic cost of the project is analyzed, section 8 presents the future work and finally, in section 9 conclusions are exposed.

2. ASV DESIGN

The ASV has been designed with flexibility and modularity in mind, choosing off-the-shelf components that can be easily replaced or even improved. Its frame components are affordable, with a good trade-off between lightness and stiffness.

The main frame has been built using aluminum extrusion profiles and the hulls with Polyvinyl chloride (PVC) piping. The watertight electronic boxes are made out of plastic for lightness with metal fixtures. This hull choice has many advantages, such as payload capacity, stability and ease of deck access (Manley, 2008). In addition, the fact that the hulls can be easily removed from the main aluminum frame structure, facilitates the vehicle transport.

The general morphology and design specifications of the vehicle are shown in figure 1 and table 1 respectively.

Table 1. Components and specifications for Xiroi ASV.

Vehicle specifications	
Battery	Lead-acid, 12V 80Ah
Actuators	Blue Robotics T200
Weight	50 kg
Size	1.6×1×0.4 m
GPS	Emlid Reach
Imu	Memsense nano IMU
ACL-USBL	Evologics S2CR 18/34
RFL	Ubiquiti Bullet BM2HP
Computer	Intel Core i5
Software	Ubuntu 16.04 and ROS Kinetic

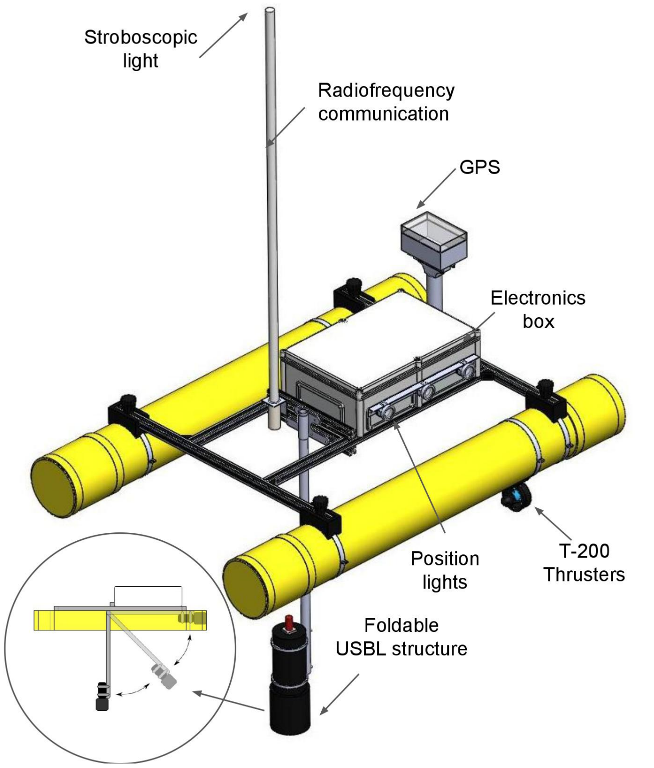


Figure 1. Xiroi ASV component description and CAD design. Note the foldable USBL structure to deploy the sensor.

2.1 Hull design

The hulls objective is to guarantee buoyancy and stability to allow a safe navigation. The size of the needed PVC pipe directly depends on the total weight the ASV needs to carry. Fixing the maximum draft of the pipes to its half to ensure stability (Thirunavukkarasu et al., 2017) and the total weight, the needed volume can be computed using Archimede's principle:

$$F_B = F_G \tag{1}$$

where F_B is the buoyancy force and F_G is the gravity force.

$$F_B = \varphi \cdot g \cdot V \tag{2}$$

$$F_G = m \cdot g \cdot f_s \tag{3}$$

where φ is the saltwater density and V is the volume of water mass displaced by the catamaran hulls. A safety factor f_s ensures stability in a moderate sea state. To perform the calculations have taken into account the data information shown in table 2

Once the needed volume is known, the length l and radius r of the pipes can be computed by (5), using the submerged height h as a parameter.

$$V = f(l, r, h) \tag{4}$$

$$V = l \cdot \left[r^2 \cos^{-1}\left(\frac{r-h}{r}\right) - (r-h)\sqrt{2rh - h^2} \right] \tag{5}$$

Given the weights in table 2, the chosen length and radius are 1,6 m and 0,1 m respectively.

Table 2. Xiroi ASV parameter for hull design and size.

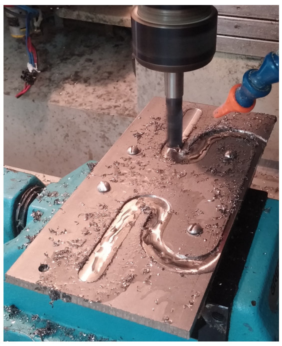
Hull buoyancy parameters	
Battery	12 kg
Electronics	4 kg
Frame	20 kg
Payload	5 kg
Safety factor	1,2
Saltwater	1030 kg/m^3
Max. draft	50 % volume

2.2 Computer-Aided Design

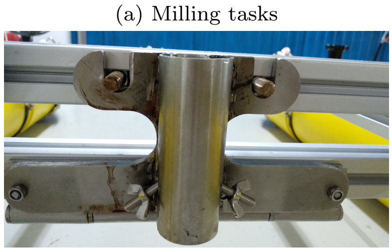
The computer-aided design (CAD) is the technology that uses computers to assist in the design of a single product. All parts of the Xiroi ASV are previously designed and tested virtually. Then, once checked the dimensions and functionality of the designed parts, they was manufactured. The main objective of the CAD is have a tool to check, test and improve the components of the vehicle before manufacturing them. Moreover, have a virtual copy of the vehicle and can add or create new parts help us to improve the functionality and versatility of the Xiroi.

2.3 Foldable USBL structure design and manufacturing

The custom hardware design of an USBL foldable structure facilitates the vehicle deployment and shallow water navigation. The previous CAD and subsequent Computer-Aided Manufacturing (CAM) techniques are used to manufacture the desired piece.



(a) Milling tasks



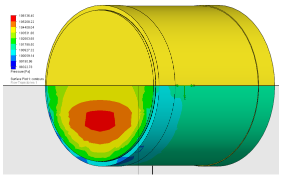
(b) Final result of the stainless steal foldable structure.

Figure 2. Milling process and final result

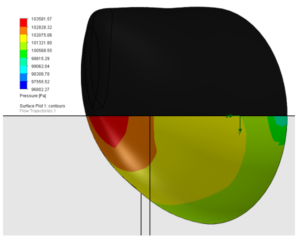
Taking into account that the vehicle will be in contact with aggressive marine environments stainless steel has been used to manufacture the foldable structure. A Fagor Odissea milling machine is used to perform the stainless steal piece. Moreover stainless steal welding and screws have been used to join the different components of the foldable structure. The milling process and the final results are shown in figures 2a and 2b respectively.

2.4 Bow design and manufacturing

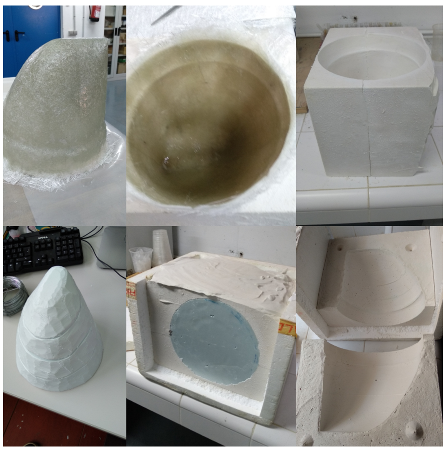
In order to reduce the drag force and increase the vehicle hydrodynamics a bow has been designed. This elements are fixed in the front of the PVC hull pipes avoiding, in this way, the direct contact of the water with a plane PVC pipe surface. A flow simulation CAD test has been applied to prove the functionality of the desired bows versus a flat surface. The extracted results are shown in figure 3.



(a) PVC pipe flow simulation, with 0.397 average friction force.



(b) Designed bow flow simulation, with 0.181 average friction force.



(c) Final result of the bow manufacturing process.

Figure 3. Flow simulation friction force results, extracted from Solidworks flow simulation CAD program and the final result of the manufactured bow.

The flow simulation was performed with the same rugosity and fluid velocity in both cases. The average friction force obtained proves that using the designed bows we can reduce the drag force improving in this way the efficiency of the navigation.

The process to manufacture the bows was divided in four parts. In the first part of the process a positive bow design was manually sculpted with polystyrene foam. Then a negative plaster mold was made. Finally we use the plaster mold to manufacture the bows using fiberglass. To guarantee a better final appearance the bows are painted.

2.5 Electrical and electronical schematic design

The hardware design of the vehicle is conformed by several electric, electronical and process unit devices. All the components used in this field are easy to find in most stores which are an advantage if you want to replace or improve them.

On the one hand the process unit devices, which are the main PC control board and the Arduino Duemilanove, have the purpose to manage the sensor input data and send the output signals according to the navigation software that will be running at the moment.

On the other hand, the electric layer is based on many components responsible of manage and distribute the electric power to the different parts of the vehicle. In this layer should be highlight devices as the ATX power supply which regulates and provides energy from the battery to the PC or the shield relay plugged on the Arduino Duemilanove which controls the lights and send signals to the thrusters. Other components included in this layer are the 12V DC to 24V DC converters used to power the ACL system and the thrusters ESC's.

Finally the sensors and actuators compose another layer that have the function to act depending of the provided orders from the process unit devices. In this way the GPS or IMU provide information and the T-200 thrusters execute the commands sent from the PC. In this layer there are included some other hardware components related to the different communication links as ACL, RFL or Umbilical wired connection. Moreover the position and stroboscopic lights provides information about the position, orientation and the state of charge of the vehicle during the missions.

All this devices were enclosed in a watertight box which have the main purpose to prevent sea water to contact them.

The figure 4 shows the schematic of the different layers that involves the electric and electronic hardware.

3. HARDWARE

As shown in figure 5, the ASV has been designed with a modular structure which facilitates maintenance and hardware modifications. All the electronics devices including the power supply are located in a watertight box fixed to the main frame. Several through hull connectors isolated with epoxy provide watertight cable routing to the external sensors and actuators.

3.1 Propulsion system

Two BlueRobotics T200 brushless thrusters move the ASV. This differential drive configuration allows the correct navigation and manoeuvrability to the vehicle. This motors, characterized and designed to run at 12V or 16V had not enough thrust to move the vehicle at the required velocity to follow the AUV. Its voltage input had to be increased to 24V to obtain 9kg of thrust that ensures enough power to follow the AUV. The actuators force at 24V input power has been characterized. The results of the thruster characterization are shown in the follow figure 6(b).

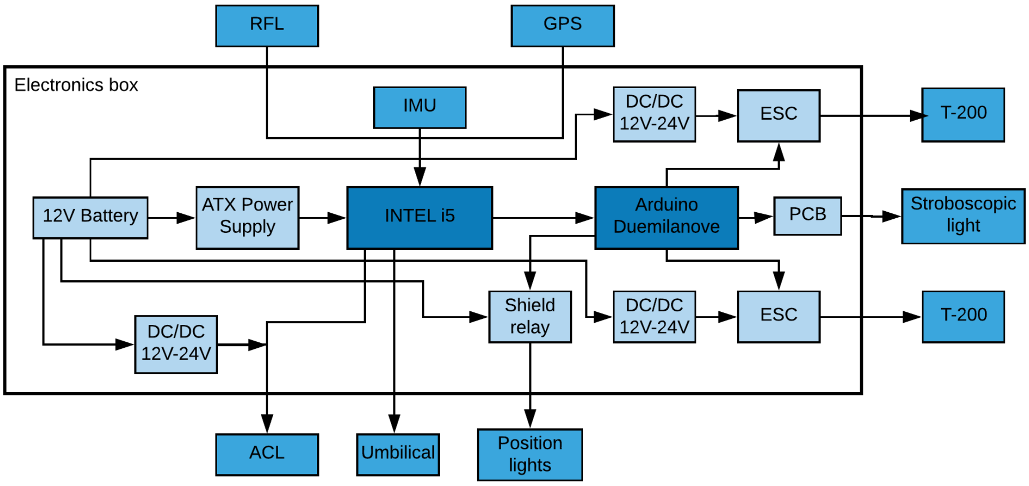


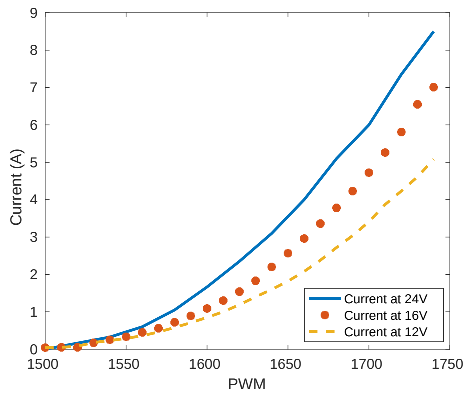
Figure 4. Electrical and electronical schematic design. In dark blue control process units devices are displayed. In light blue are shown the electronical components. Finally sensors and actuators are displayed in sky blue

Figure 5. Xiroi ASV at the outdoor pond where the experiments were performed.

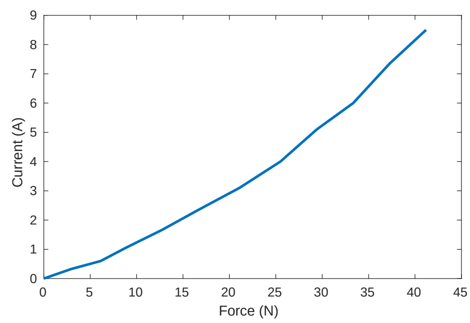
Moreover in the figure 6(a) can be seen the current evolution depending the PWM input signal provided by ESC's. As expected, the higher PWM signal obtains the higher current consumption. Moreover, in figure 6 (b) is shown the thrust evolution depending on the current input.

Two dedicated converters power the Electronic Speed Control (ESC) that control the T200s at 24V up to 20A. An Arduino microcontroller board is used to convert the computer Revolutions Per Minute (RPM) requests to Pulse Width Modulation (PWM) signals to the ESCs.

To prevent a suddenly current rise or fall, which could damage the ESC's or the thrusters, a software limitation is applied before sending the signal to the propellers. This software limitation is based on a slew rate, where the falling and rising rate are prefixed to restrict the signal and prevent the propulsion electric system from overcurrents.



(a) Current evolution versus PWM signal applied to the thrusters at different operative voltages. Blue line represents the current evolution at 24V versus the PWM signal applied



(b) Force evolution versus applied current at 24V

Figure 6. Bluerobotics T-200 thrusters characterization at 24V input voltage

3.2 Power supply

The vehicle energy is provided by a 12V 80Ah lead-acid car battery located inside the main box. This power supply have the main purpose to distribute the needed electrical power to the different components. A series of DC/DC converters were added to reach the different required voltages. In the follow table 3 is shown the power consumption of the different devices which composes the electronic part of the vehicle.

$$P = 523\Delta\gamma = 627W \tag{6}$$

Where 523W is the estimated total power consumption extracted from table 3 and γ the security factor to ensure the required power fixed to 1,2. The needed current can be computed using Ohm's law as follows.

$$I = \frac{P}{V} \tag{7}$$

Given the main voltage as 12V and the total power extracted from 6 can be determine that the vehicle required instant current ascends to 52A. Assuming that the capacity of the lead-acid car battery is 80Ah we can compute the full power operating time of the vehicle as follows.

$$Time = \frac{80Ah}{52A} \approx 1,5h \tag{8}$$

This operation time assumes that the T-200 thrusters, which are the biggest consumption source, were running all the time. This assumption is not correct because the use of the thrusters are related to the navigation behaviours. Despite the oversizing, we can ensure the required power about two hours missions.

Table 3. Xiroi ASV power consumption.

Power consumption					
	5V	**12V**	**15V**	**24V**	**Watts**
PC		2.5A			30
T200L				8,5A	204
T200R				8,5A	204
GPS				0,5A	12
ACL				2,5A	60
Lights			0.4A		6
RFL		0,5A			6
IMU	0,14A				0,7
Total					523

3.3 Navigation sensors and computer

For an ASV, a Global Positioning System (GPS) and a compass are the minimum sensor set required (Caccia et al., 2008). In our case, we use a Global Navigation Satellite System (GNSS) based on GPS and Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) using a source of Differential Global Positioning System (DGPS) or Real Time Kinematic (RTK) corrections to improve data positioning signal. An Emlid Reach GNSS provides latitude and longitude position estimation. This device is individually placed in an smaller watertight box with its antenna fixed to a ground plane to provide shielding and ensure signal reception requirements.

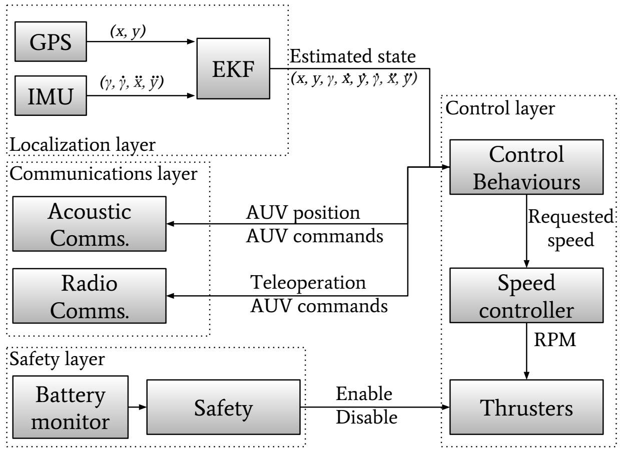


Figure 7. Xiroi ASV software architecture using ROS

For compass, an Inertial Measurement Unit (IMU) with magnetometer is chosen. The acceleration, rotational speed and heading provided by a Memsense nano-IMU.

Finally, the vehicle on-board computer consists of an Intel i5 processor with 4Gb of RAM. It manages the input information and acts consequently to execute a mission, which will be explained in section 4.

4. SOFTWARE FRAMEWORK

The platform has been programmed in *C++* and *Python* using Robot Operating System (ROS) under *GNU/Linux*. The ASV software has been divided in several modules or layers: (i) communication, where the ACL and RFL allow teleoperation mode and act as a link with ACL sending AUV commands, (ii) localization, where all sensor are read and the ASV state is estimated using an Extended Kalman Filter (EKF), (iii) control, where depending on the desired behaviour of the ASV a requested speed is commanded and (iv) safety, where battery voltage and safety lightning are monitored and the different main input data acquisition are verified. The different systems are defined as ROS nodes connected through topics. Driver libraries such as for the IMU, GPS or the thrusters have also been ported to ROS. The whole system can be seen in figure 7.

4.1 Localization

The GNSS and the IMU data are fused in a standard Extended Kalman Filter (EKF) provided by (Moore and Stouch, 2014). The imputs used are latitude x and longitude y from the GNSS, and orientation γ, orientation rate $\dot{\gamma}$ and linear accelerations $\ddot{x}, \ddot{y}$ from the IMU. These readings are used to predict and update the EKF whose state vector is $(x, y, \gamma, \dot{x}, \dot{y}, \dot{\gamma}, \ddot{x}, \ddot{y})$.

Prior to the EKF, the IMU is filtered to increase data quality using Sebastian Madgwick's IMU filter (Madgwick et al., 2011).

4.2 Communications

The principal reason to design and build this platform is to ensure stable communication and localization to a

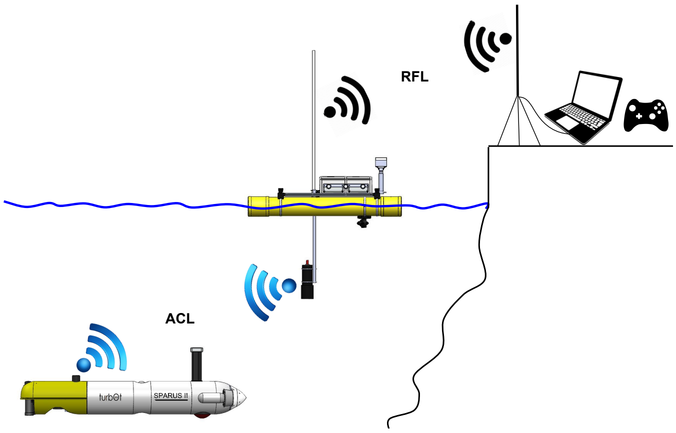


Figure 8. Communication links from the operator (on the shore) to Xiroi ASV through radio frequency, and from the ASV to Turbot AUV through acoustics.

submerged AUV during a mission. Therefore, the ASV has to provide two links, these communication links are represented in figure 8.

The USBL, fixed to the aluminum main frame, permits ACL communication with the AUV. Its fixture was made using a hinge and an extensible rod to fold compactly the sensor during deployment and adjust it depending on mission requirements and the sea floor characteristics. This mechanism is shown in figure 1

(1) *ASV to AUV*: The link to the AUV is performed using a USBL modem. The device not only communicates but also localizes the position of an acoustic transponder with respect to the USBL head. Since the absolute position of the USBL head is known thanks to the estimated ASV state, the absolute position of the AUV can be known, and it is fed to its own EKF in the AUV for precise localization (Guerrero-Font et al., 2016). The distance between the ASV and the AUV has to be as reduced as possible to reduce the echoes and reflection effects and improve the acoustic communication.
(2) *ASV to operator*: Even if the ASV is well communicated with the AUV, the support team should also be in range to be able to *see* the AUV in order to command it. Therefore, the ASV is equipped with a long range outdoor omni-directional antenna TL-ANT2412D, capable of establishing a 2.4 GHz communication link at over 5 km.

The operator can also send speed requests to the control architecture of the ASV using a remote controller. It allows the operator to maneuver the vehicle and place it at an specific location or move it remotely if is it necessary, which is essential to perform the keep position behaviour or just to fix the start of a mission.

A safety and positioning lightning system helps us to know where is the ASV and what is the State of Charge (SoC) during sea operations. Portside has red Light Emitting Diode (LED) lights and starboard green lights. The light on/off state is controlled through a relay by the Arduino Duemilanove microcontroller. Furthermore the ATX power source placed in the electronics box provides information about the state of charge of the battery. We use the SoC data provided through an stroboscopic white LED placed on the top of the ASV as a visual link to give information using blinking flash patterns so the operators can receive direct information about the ASV state and position.

4.3 Control

In the control layer the reception of the minimum sensors data as IMU, GPS and ATX power source are verified to satisfy the correct initialization of the vehicle. A buffer of data inputs are implemented in order to ensure the convergence of the IMU and GPS data. Through the data provided from the ATX power source, a minimum SoC threshold are fixed in order to allow the operation and prevent a system shutdown. Once the data have been received correctly the system could initialize the navigation.

4.4 Teleoperation

The teleoperation mode allows the remotely teleoperation of the vehicle through a RCL between the base station and the ASV. A logitech f710 wireless gamepad are used to send commands and operate the vehicle. In order to provide useful navigation capabilities the gamepad buttons are used to send navigation services as enable or disable thrusters or enable or disable keep position. Finally the right gamepad joystick sends joy commands to the T-200 thrusters which are used to manoeuvre the vehicle remotely.

4.5 Safety

Safety layer have the purpose to maintain a continuous monitoring of the essential input data as GPS, battery SoC, RCL or the maximum thruster current during the missions. In this layer all these values are checked and act consequently depending of the fixed thresholds. If the values aren't satisfy the conditions the safety layer sends a disable thrusters service stopping immediately the mission.

5. NAVIGATION BEHAVIOURS

The software architecture implements different types of navigation behaviours depending of the mission requirements: follow a list of waypoints, track an AUV or keep position. In these three cases, given a desired waypoint $\hat{\boldsymbol{x}} : (\hat{x}, \hat{y}, \hat{\gamma})$, and the current ASV position $\boldsymbol{x} : (x, y, \gamma)$, both expressed in the same coordinate system, we first compute the distance (d) and orientation (α) of the waypoint with respect to the ASV as depicted in (9)-(10), and shown in figure 9.

$$d = \sqrt{(\hat{x} - x)^2 + (\hat{y} - y)^2} \tag{9}$$

$$\alpha = \gamma - \tan^{-1}\left(\frac{\hat{y} - y}{\hat{x} - x}\right) \tag{10}$$

From these two values, the thruster setpoints can be computed using

$$v_r = k \cdot v_{\max} \cdot (\cos(\alpha) + \sin(\alpha)) \tag{11}$$

$$v_l = k \cdot v_{\max} \cdot (\cos(\alpha) - \sin(\alpha)) \tag{12}$$

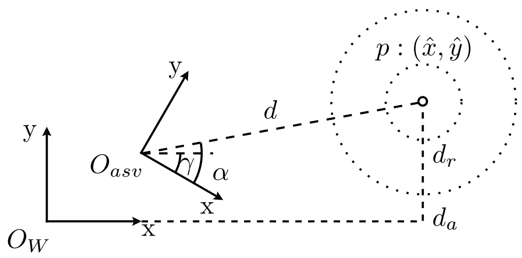


Figure 9. Given a destination point p and the ASV position r in a world coordinate system O_W, the computation of the angle α is needed to reach the desired waypoint.

where,

$$k = \begin{cases} 1 \text{ if } d \geq d_a, \\ 0 \text{ if } d_r < d < d_a, \\ -1 \text{ if } d \leq d_r. \end{cases} \quad (13)$$

this conditional gain k switches between moving towards the target, waiting or moving away from the target (e.g. in case of plausible collision).

The coordinate system used in these equations is depicted in figure 9, where the ASV shown as O_{asv} with a given position and orientation with respect to world coordinates O_W, aims to achieve a goal point p at a heading α with respect to O_{asv}.

5.1 AUV tracking

The main objective of Xiroi ASV is to follow Turbot AUV while keeping a safety distance. This distance must ensure that the acoustic communication is not broken and that the acoustic path lies in a cone with its vertex in the AUV, its axis vertical and an aperture of 30 degrees. However, the ASV should not be just on top of the AUV while it is surfacing. The acceptance distance (d_a) ensures ACL quality and repulsion (d_r) prevents the ASV from colliding into the AUV when surfacing.

The ASV receives the AUV position through the ACL, then once received, the ASV can compute the setpoints thruster signals to follow the underwater vehicle.

5.2 Waypoint following

Xiroi ASV must reach a list of prefixed waypoints one after the other. The mission concludes when the last waypoint is achieved. In this case, the repulsion distance is set to zero. Using this kind of navigation strategy the operators can send a predefined mission to the ASV with the aim of explore a specific region or take samples of desired areas.

5.3 Station keeping

This behaviour adds flexibility and safety during operations. Xiroi ASV is commanded to keep its own position within a threshold defined by the acceptance distance d_a, the ASV must counter-act any drift source and keep itself at the same spot. Enabling this mode at any time provides not only a safe way of deployment for another vehicles or to fix the USBL position during small-size AUV missions, but also gives the operator flexibility to send the AUV and ASV away from the shore where the water is too shallow. Like in the previous behaviour, the repulsion distance is set to zero since there is no risk of collision.

This kind of behaviour helps to improve the mission requirements and overcome some setup communication issues like the transceiver cable length or the multipath caused by the reefs.

All this navigation behaviours has been transformed in ROS nodes which are included in the software documentation folder.

6. FRAMEWORK TESTS

To test the effectiveness of the behaviours exposed earlier, a series of experiments are conducted in order to check the ASV control framework.

First, the control framework is tested under simulation using data recordings from AUV missions and finally Xiroi ASV is tested in an outdoor pool to check the correct operation of the navigation behaviours.

6.1 Simulation tests

Using a previously recorded Turbot AUV trajectory, the simulated Xiroi ASV follows the AUV with an acceptance distance of 5 m and a repulsion of 3 m, as explained in 5.

The trajectory of both robots is shown in figure 10a, and the distance of the ASV to the AUV in figure 10b. At the beginning, the ASV is far from the AUV, and moves towards it until its distance is below the threshold of acceptance (5 m). Since the AUV is still moving, at second 700 a collision may happen and the ASV moves away from the path. Once the risk has been avoided, the ASV follows the AUV as designed.

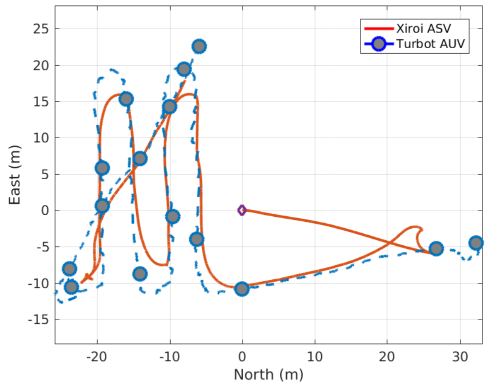
6.2 Pool Trials

Pool trials are performed in a $40 \times 40m$ outdoor pool, where the waypoint follower and station keeping navigation behaviours explained in section 5 are tested.

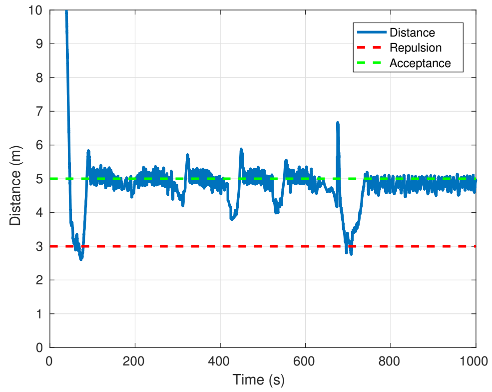
(1) *Station keeping*: Figure 11 shows results from the station keeping test behaviour. In this navigation test the goal position and threshold distance are prefixed at 2.5 m. As seen in the down image, the command thrusters increases when the ASV reaches the prefixed acceptance distance threshold. In order to force the behaviour to run, the vehicle was periodically pulled away from the goal point.
(2) *Waypoint follower*: The waypoint follower behaviour results are represented in figure 12. Despite the external disturbances, the Xiroi ASV reaches every predefined waypoint one by one. The prefixed waypoint acceptance radius is fixed at 2 m.

7. ECONOMIC STUDY

Xiroi ASV has been designed with flexibility and modularity in mind, choosing common materials that can be easily replaced or even improved. Moreover using this kind of materials, the total material cost can be reduced in



(a) Trajectories of the ASV and the AUV. Note that the ASV starts at $(0, 0)$



(b) Distance from the ASV to the AUV under path following behaviour.

Figure 10. Simulation of Xiroi ASV following a recorded Turbot AUV path.

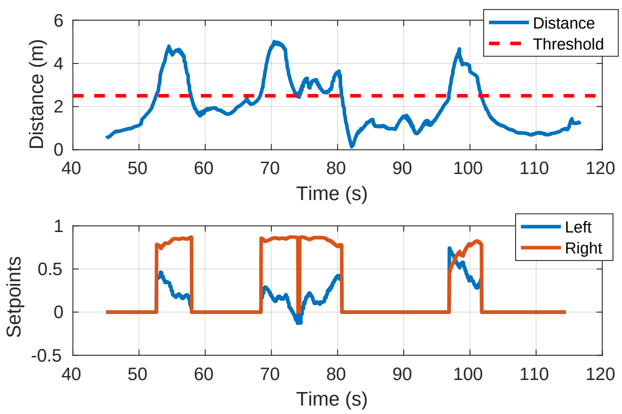


Figure 11. Distance from Xiroi ASV to predefined waypoint and its acceptance threshold (top) and thruster commands (down). When the distance to the waypoint is bigger than the threshold, the command is to move towards the goal.

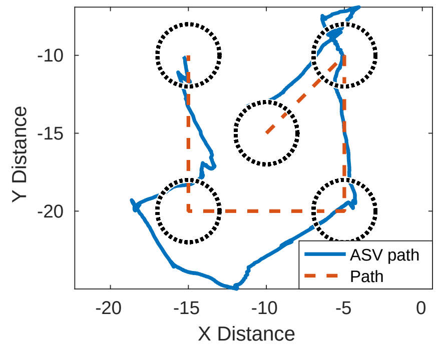


Figure 12. Xiroi ASV follows a list of waypoints. Blue line shows the ASV path during the waypoint follower behaviour, each waypoint is shown by a black circle and desired path is represented as dashed red line.

order to create an inexpensive vehicle as a final result. Some materials used in the vehicle have been reused from different robotics projects. Materials like Intel Core i-5 PC, Memsense IMU sensor, ATX power supply, the position lights, the Arduino Duemilanove microcontroller or the ethernet switch are included in this kind of reused material. However there are many other equipment that have been purchased to build the vehicle. Below are detailed the cost of the used materials to perform the Xiroi ASV.

Table 4. Material cost.

Material cost	
Lead-acid battery	100€
Actuators	286€
ESC's	42€
12V-24V DC/DC's	65€
Vehicle frame	120€
RCL	150€
Underwater links	430€
Other materials	50€
	1243€

Although the design and manufacturing process of the vehicle and the software control implementation has consumed a time that must be taken into account in the economic study. The design and development of the vehicle has been extended during four months. The estimated invested time in the different ASV manufacturing work processes is shown in the follow table.

Table 5. Invested time.

Invested time	
Hardware design	40h
Hardware manufacturing	90h
Software implementation	190h
	320h

Taking into account the total time invested extracted from table 5 we can compute the work cost assuming that the minimum base salary for an industrial engineer is fixed to 1521€(as detailed in BOE-A-2018-2824). The personal work cost is 2028€.

Finally, the total economic cost of the vehicle amounts to 3271€

8. FUTURE WORK

The design and development of an ASV platform are shown in the previous pages where the preliminary configuration of a development vehicle have been described. Some parts of the vehicle like power endurance, the software motion controller or weight efficiency among other vehicle features should be improved.

In order to reduce the total weight, increase the power endurance and in this way enhance the operation time a lithium polymer battery pack can be installed in the main electronics box. Another possibility is to use alternative energy sources, like solar or wind energy, to recharge the battery during the navigation and allow to increase the mission operation time.

The motion controller, nowadays based on a quite primitive principles, could be improved taking into account more advanced motion controller alternatives with the aim of improving the navigation behaviour.

Throughout the design, manufacturing and testing process some improvements have been applied to increase the ASV operation capabilities. In order to provide the ASV with the ability to be used to seafloor exploration a Bumblebee stereo camera was fixed in the foldable structure. Using this new input sensor we can reconstruct the seafloor and create a 3D image using a RtabMap (Labbe and Michaud, 2013) reconstruction software adapted to the camera specification.

Finally, next experiments will include testing these basic behaviours in the sea, track an AUV in real time and provide communication between the operation area and the rover.

9. CONCLUSION

The main objective of the Xiroi is reached, an affordable, inexpensive, functional, modular and operative ASV has been created.

The hulls and frame structure design has proven to be strong enough to ensure the correct buoyancy and vehicle integrity. The structure have been tested in different navigation conditions and the results has been successful.

The electrical and electronics hardware were designed and fixed into the watertight box to be robust enough to ensure it correct functionality freely of the maritime conditions.

Depending on the payload configuration the vehicle has the ability to be used in different missions such as AUV tracking, seafloor inspection or water analysis.

The Xiroi ASV is capable to do different types of navigation behaviours depending of the specific mission necessities in order to reduce the common acoustic drawback problems and carry out the mission objectives.

An autonomous surface vehicle has created that has the ability to follow the AUV closely and improve the acoustic signal communication, reduce personal operation, the vehicle is modular and with many different payload configuration. All these characteristics allows a wide variety of possibilities to improve join missions with the AUV. Moreover the ASV has the ability to do solo missions.

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