Towards the electromechanical design of an autonomous robotic sailboat

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***Abstract* - Due to numerous global influencing factors such as climate change, water quality, population growth, geopolitical disputes over territory among others, the world never looked so closely to our oceans. With the recent development of unmanned craft, demands such as water and marine borders monitoring can now be met with relatively low cost. A problem yet be solved in this kind of mission is the supply of power for the robotic systems given the difficulty of continuous supplying hundreds of vessels in the ocean. Therefore, this work proposes techniques and tools for the development of an automated sailboat driven primarily by wind power combined with a power system that is capable of generating electricity through photovoltaic cells located on the deck of the boat and stored in a bank of nautical batteries. Both the electronics and the electromechanical parts present in the aquatic vehicle are autonomous and therefore do not require the boat to return to land for a systematically refueling.**

Keywords - AUV, Robotics, Sustainable Energy, Embedded Systems, Photovoltaic Cells.

I. INTRODUCTION

Due to world recent factors as the increasing exploitation of natural resources, the decreasing of the quality of drinking water, or even because of territorial integrity issues, the oceans have been seen as a priority resource by several nations and international organizations [1]. Another concern of researchers refers to the fact that the ocean environment has special features such as being an automatic global temperature controller, on the ground. Several studies have already indicated that a breakdown in this so important system may eventually occur in the near future, and that if it occurs would be irreversible. According to Lovelock, with a disordered global warming, much of the land would become a tropical savanna or desert, adding to the 40% of land already devastated by humans for food production purpose [2].

All of these factors suggest the need of an immediate follow-up (monitoring) of the evolution of the parameters that are commonly used to evaluate and determine the health of our seas. Indeed, much has been done but there is still so much to work for the development of automated and robust monitoring systems able to perform various tasks automatically in rivers, lakes, and oceans. In this context, in order to meet this growing demand for research and monitoring of water surfaces, several nations have made considerable investments in research for development and improvement of Autonomous Underwater Vehicles (AUV) and Autonomous Surface Vehicles (ASV) the last also known as Unmanned Surface Vehicles (USV). We are mainly interested in ASV that are vehicles that operate on the surface of the water (watercraft) without a crew. Over the past two decades, these vehicles have decreased in size and cost and developed into a versatile equipment nowadays used for commercial, industrial, environmental, military and even political applications. Figure 1 shows the percentage distribution of manufactured ASV and UAV in the world by 2009 [3,4].

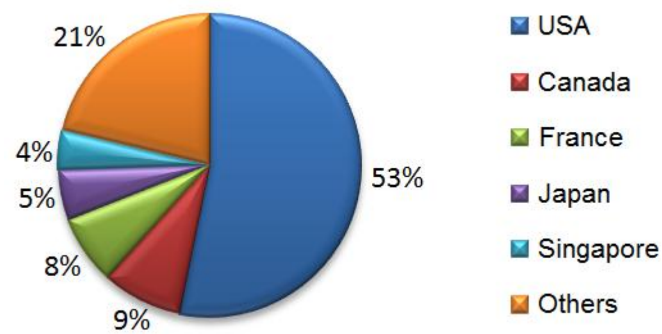

Figure 1. AUVs Manufacturing of countries, adapted from Gafurov (2015) [5].

The first AUV as we noticed has been designed and developed in 1957 in the US. Called SPURV (Special Purpose Vehicle Underwater Research) it was built in order to carry out research in the Arctic waters [6]. Scientists at the University of Washington have developed in the 80s, the SPURV II, which had more sensors and the ability of being controlled by a computer fitted to an oceanographic ship [5,7]. Other research groups have developed their prototypes, with their improvements and peculiarities, but it is only in 1987 that the AUV called ARC, is built with the capacity to stay under water for some 35 hours through the combination of new navigation systems, an optimization in algorithms, and new types of batteries [5,8]. From 2002 over, due to technological advances, the ARC were retired. It is estimated that over 18 years of operation they have conducted more than 800 missions [8].

TABLE I. MAIN AUVS DEVELOPED UNTIL 2003 [5].

Model	Year	Weight (Kg)	Length (m)	Autonomy (h)
SPURV	1957	484	3,1	4,5
SPURV II	1973	598	4,5	5,5
L-1	1979	1140	4,3	6,0
ARCS	1987	1360	6,4	10,0
REMUS-600	2003	240	3,2	24,0

In September 2009, the Department of Natural Resources of Canada ordered two UAV with capacity of submerging to 5000 meters deep. Within the next two years they were posted into the Canadian Arctic to conduct surveys of the ocean floor [8]. Missions like this one have becoming increasingly tangible coming up with autonomous maritime systems including submarines, UAV and ASV gliders that will revolutionize our abilities of mapping and monitoring the oceans [4].

Figure 2. UAV mission in Canadian Arctic [8].

Today UAV are capable of carrying a variety of cargo (payloads) which may include instruments and sensors geophysical, geochemical, oceanographic, and acquisition of high-definition imaging tools. Additionally, these devices have abilities as analyzing and storing a vast amount of data continuously, uninterruptedly for several long-duration missions [4, 9].

However, it still remains the problem of power supply for these robotic systems mainly driven by the difficulty of continuous supply of vessels in the ocean. Corroborating with us, Alam *et al.* [3] state that the growth of UAV and ASV applications greatly increases the importance of these energy efficient vehicles, since, often missions are compromised due to the limited energy storage capacity of batteries. Regarding the limitation of autonomy of the UAV, Yuli and Jiajun [10] state that, regardless of the type of engine used for propulsion, the major limitation of these craft is the maximum distance one can travel on a single mission. As stated in their paper, they have solar energy as a possible solution to resolve the conflict between distance traveled and energy spent in this type of system [10]. Experiments carried on the possibility of installing solar panels on UAV and ASV have shown promising results, since a hybrid surface and underwater vehicle, an SAUV, could operate autonomously by the ocean over a period of weeks or months in night missions, while reloading the batteries during day by sunlight [11].

On the other hand, a solution to the problem of autonomy may be the use of a wind generated by the propulsion, through the use of sails, like in a small-sized traditional model sailboat. After all, sailing is one of the oldest techniques that humanity prepared to solve the mobility problem over long distances, or that required to cross lakes, rivers or oceans. In recent years, some researchers have developed robotic systems of this nature, mainly in order to participate in competitions as Microtransat and WRSC (World Robotic Sailing Championship), which consist of performing autonomously crossings across the ocean (Figure 3). Between others, one can find the ASV Roboat, built by the team of INNOC [12], the FAST developed by researchers at the University of Porto [13] and the Avalon, designed by ETH-Zurich [14].

Figure 3. Robotic sailboat participating in the WRSC 2014 [15].

In the same direction, in the current work we propose the design and construction of an autonomous robotic sailboat named N-Boat, which consists of solving the following main problems:

A. design and construction of the vessel, made of fiberglass;

B. control of boat actuators through microcontrolled electronic interfaces;

C. development of a power-generation system and electric energy storage, basically composed of photovoltaic cells and a bank of nautical batteries;

In this way, it is believed that such ASV may be able to perform, independently, both in short and long duration missions without the need for replenishment.

II. The N-Boat Proposal

In general, in the case of navigation systems in aquatic environments, the most important forms of energy available are wind, solar and tidal. With regard to propulsion, vessels that use the wind propelling force as the primary source are termed sailboats. The sails are responsible for transferring the wind force for boat propulsion not depending on the engine for this purpose. According to Belcher [16], the use of boats propelled by the wind is the best alternative for long-term tasks.

Figure 4. ASV: construction steps of the N-Boat II.

Our main goal with the N-Boat is to develop a comprehensive project aimed at the construction of an autonomous sailing robot, designed to perform various missions, with different purposes. The N-Boat I prototype is a sailing autonomous nautical model, able to receive information from position (GPS) and direction (windsock, compass) sensors, and to trace out a route between two or more points. For that, it has to basically control the sails and rudder through servomotors and communicate with some base station on land in order to carry out a movement task in the sea, rivers, ponds and lakes. To do this course direction, it uses energy stored and provided by a 12V battery. Fuelling the energy cells has to be an autonomous task.

The N-Boat II prototype is a customized sailing boat, measuring 2.5m in length, with the following subsystems: perception (cameras), navigation (GPS), control (actuators), communication (GPRS and radio frequency); security (sensors and alarm), memory, payload (monitoring system of water quality), and power fuelling and storing (photovoltaic cells and batteries). Figure 4 shows some stages of construction of our ASV. In general, semi and autonomous navigation systems have three main layers: Perception, Navigation and Control. According to Thrun *et al.* [17], these systems can also be organized into five major functional groups including: interface with sensors, perception, control, vehicle interface and user Interface. It is important to stress that even without a standard architecture that defines mobile autonomous systems, it is possible to present the most common steps to these systems, where each of these layers has an energy demand to be met [18].

Figure 5 presents a more comprehensive summary for these subsystems (layers), which are named according to their functionality.

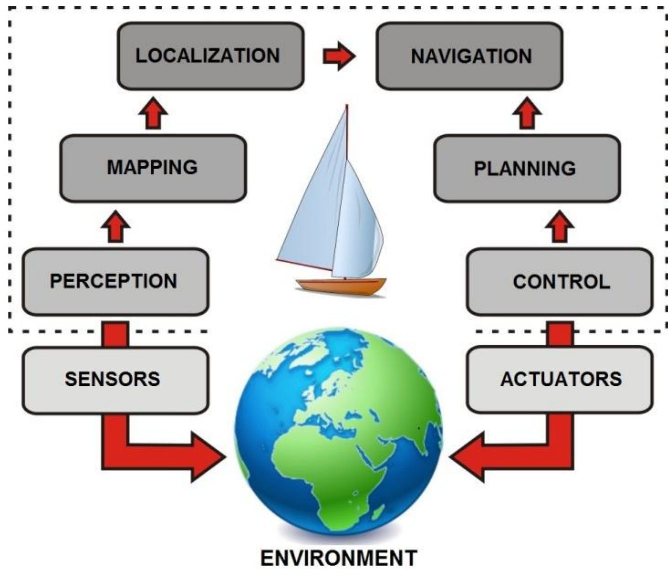

Figure 5. Layers of an autonomous navigation system.

III. Actuators Control

The N-Boat sailboat robot has the sail and the rudder as the responsible elements, respectively, for propulsion and steering of the vessel. To control them, the installation of actuators is a necessary task mainly for replicating human intervention in conventional sailboats.

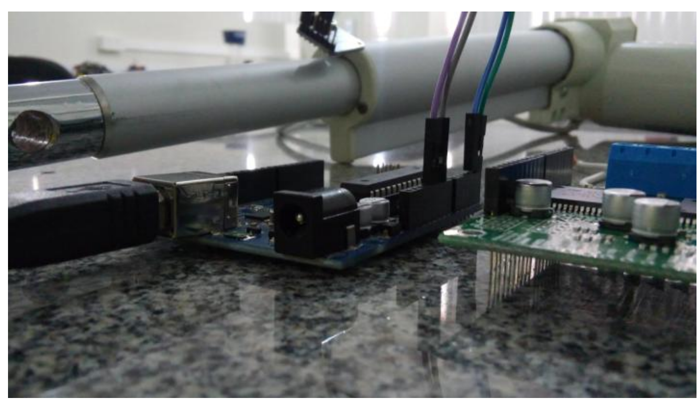

Figure 6. Actuators robotic sailboat during the bench tests.

To move the sail handler, which restricts the angle of the sail to the wind, it has been installed a 12V electric winch with the capacity to pull up to 680 kg. As for positioning the rudder in the desired direction, we use a linear actuator (12V) with linear range of 50cm and ability to push or pull up to 120kg.

The characteristics of these actuators were previously defined through the manufacturer's manuals and validated in bench tests that were performed in the laboratory. It was possible to check several variables, such as the consumed current and power dissipated by each of the devices, as seen in Figure 6. Table II presents the detailed characteristics of the actuators based on the results obtained during this bench testing.

TABLE II. CHARACTERÍSTICS OF THE USED ACTUATORS.

	Eletric Winch	Linear Actuator
Operating voltage	12 V	12 V
Consumed current*	4,2 A	2,5 A
Peak current*	7,0 A	4,0 A
Speed	2,7 cm/s	8 cm/s
Capacity	680 kg	120 kg
Function in sailboat	Mainsheet	Sail Tiller

* The value may rise with increasing of the load on the engine.

For the low-level control of these actuators, we developed an electronic interface consisting of a microcontrolled electronic prototyping board (using the Arduino Uno), an engine control drive (VNH5019 shield motor), and sensors used for positioning, as a color sensor (TCS34725) and a rotational encoder (KY-040). The VNH5019 motor drive it is a device for bidirectional control of high-power engines. This board has a pair of robust CI VNH5019, operating from 5.5V to 24V and can drain up to 12A continuous per channel, with peak 30A. Another relevant factor in this device is its versatility, since it can be used with Arduino boards, in their shield configuration, and also as a common drive for any other microcontroller. It also has an option for combining its two output channels for engines when in dual channel mode so only one output up to 24A continuous (60A peak) in single channel mode [19]. Figures 7 and 8 shows a diagram with the different possibilities of VNH5019 motor drive settings.

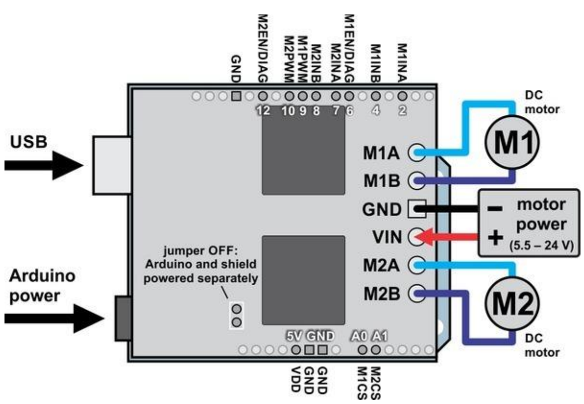

Figure 7. VNH5019 Motor Shield working with the shield in dual channel mode.

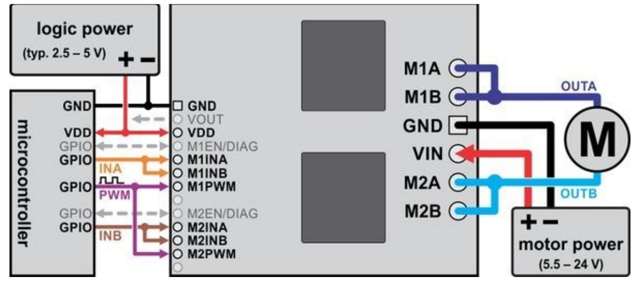

Figure 8. VNH5019 Motor Shield working as an external device, in single channel.

IV. THE POWER SYSTEM

Even though it does not depend on the engines to proceed forward (the wind does it), the N-Boat needs electricity to meet the demands of the various devices (electrical and/or electromechanical) which make up each of the subsystems. It is important to highlight that the ASV consumes power even during wind engine, since in order to get control of its trajectory it is necessary to control the sails and rudder actuators. Also, all of the sensing and positioning subsystems also need electricity to operate. This demanding power is provided by photovoltaic cells installed on the deck.

There are several possibilities regarding the power of embedded systems in ASV. The offshore wind turbines are devices that transform this energy into electrical energy, which may be vertical or horizontal axis [20]. In its turn, the hydro utilizes the wave energy which comes from underwater and/or the speed of the boat's motion currents. At the same direction, solar energy can be transformed into electricity by installing photovoltaic panels [10,21].

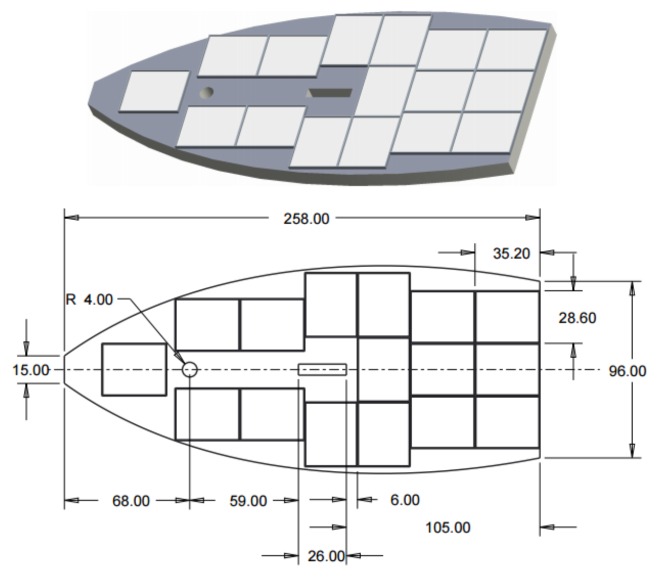

Figure 9. Arrangement of the photovoltaic cells over the UAV.

In this project, we have chosen for using solar energy for the supply of the power responsible for the energetic support of our automated sailboat. Thus, taking advantage of the free deck area, 16 solar panels are installed, arranged in an initial configuration with further optimization as possible. Each board has approximately 35 cm by 28 cm. Figure 9 shows the layout of installation of these cells on the boat deck. In this context, the power consumed by this vessel becomes for this article an important object of study, to the extent that this data affects directly the development of the system proposed. Table III shows the estimated power consumed by the components of the vessel. It is important to note that the consumption of electronic circuits and sensors will be minimal compared with the consumption of the main actuators installed in the sailboat.

TABLE III. ESTIMATED CONSUMPTION OF THE N-BOAT-II COMPONENTS.

Componente	Power (W)	Quantity	Total (W)
Linear actuator	30	1	30
Mini eletric winch	50	1	50
Video card	5	2	10
Estereo camera	10	1	10
Communication board	2	1	2
Control board	2	4	8
Payload	12	1	12
GPS, Compass	1	1	1
Windsock	1	1	1
Solar charge controller	3	1	3
		Estimated total	127

A. Solar photovoltaic module

As already mentioned, these devices are responsible for the transformation of solar radiation into photovoltaic electricity. As we could find out, in the market there are numerous sizes and designs, each one of them fitted to a specific requirements that depends on each project specification. In our project, we adopt the KM module (P) 10 of Polysilicon Kyocera. A summary of the main features is presented in Table IV.

TABLE IV. CHARACTERISTICS OF SOLAR CELL [22].

Especifications	KM(P) 10	Units
Rated Power	10	[W]
Output voltage	17,4	[V]
Output current	0,58	[A]
Module efficiency	10	[%]
Module dimensions	352x286x22	[mm]
Weight per module	1,4	[kg]

B. Solar charge controller

The photovoltaic charge controller is responsible for finding the maximum electric power point to a particular arrangement of photovoltaic cells and thus deliver the current needed to charge the batteries. For this reason, many devices use the MPPT algorithm (Maximum Power Point Tracking) which constantly adjusts the arrangement of the operating point.

Being a versatile and robust device, which meets the N-Boat system requirements, the selected driver was the XW-model MPPT60-150 brand Xantrex Technology Inc.

TABLE V. SOLAR CHARGE CONTROLLER XW-MPPT60-150 [23].

Especifications	XW-MPPT60	Units
Battery nominal voltage	12;24;36;48;60	[Vdc]
Maximum PV voltage	140	[Vdc]
Open-circuit voltage	150	[Vdc]
Short-circuit current	60	[Adc]
Power consumption in operation	2,5	[W]
Module size	368x146x138	[mm]
Weight	4,8	[kg]
Operating temperature	-20 a 45	[°C]

C. Batteries

The batteries main objective is to store the energy generated in order to supply the subsystems demand during operation. Several authors conducted an evaluation of battery systems available on the market and concluded that for applications of this nature, the lead-acid battery voltage of 12V nominal cell is the best due to factors such as power output, ease of use, relatively low cost, size, and operations security [3].

Our photovoltaic generation system capacity is about 160W under normal weather conditions with daily use of 65% that may produce 104W with a current of 8.7A to a voltage of 12V for approximately 8 hours of light per day. Thus, the maximum energy stored per day will be 69.3Ah, being recommended to select a battery that works up to 65% load (maximum depth of discharge) that is 106.6Ah.

In this way, taking into account the above data and the best value, we have chosen the Moura Boat Boating battery (with 12V and 105Ah). The power subsystem is also equipped with proprioceptive sensors, sensors power consumption and battery charging, in the second case the sensor is present with redundancy.

D. Energy efficiency

The use of energy resources, even being sustainable, should be optimized. The search for energy efficiency within the proposed robotic system has two focuses: the optimal control of the system and the use of smart strategies of consumption. Thus, there are some specific scenarios of the system operation in which it makes use of intelligent strategies for survival and more efficient management of energy resources.

Charging the batteries: in this particular case, after informing the batteries that are less than 10% of the total average consumption, the control architecture tells the system that it should go into "hibernation"; in this state, the sails are recalled and a message is sent to the base station informing the status and the position of the vessel.

Not incoming of solar cell energy: mainly at night or cloudy sky, the system must go into a pre-hibernation state, in which the sails are recalled and is turned off all the secondary subsystems.

V. Conclusion

From the results, we found that the proposed system is able to supply the necessary energy demand for the correct functioning of all devices shipped in our surface unmanned vehicle, the sailboat robot N-Boat. In this way, it is believed that such ASV may be able to perform, independently, both in short and long duration missions, without the need for replenishment or refueling.

This system allows it to be able to perform short and long-term missions without any break scheduled for refueling. Although the restriction imposed by the solar panels installed on the vessel, due to the limitation of its deck area, we have calculated, in the average conditions, an overhead power generation of about 100W.

We conclude remarking that the power consumption is directly related to specific ASV task, as shown through calculations resulting from computer simulations. Therefore, we believe in a system consumption reduction with the improvement of the low-level control and intelligent strategies used in specific situations. These and other future works such as checking the operation of the sailboat built in trial on a dune lagoon (Lagoa do Bonfim) are the next steps in this research. To achieve this, the control that is already operational from the first prototype of the N-Boat [24] is already being be implemented for being tested in the N-Boat II.

As future work, we intend to obtain a mathematical model describing the movement dynamics of the system in aquatic environments as a way to validation the proposed project.

References

[1] M de Santo, P. J. S. Jones, "Offshore marine conservation policies in the North East Atlantic: Emerging tensions and opportunities," *Marine Policy*, vol. 31, pp. 336-347, 2007.

[2] J. A. Lovelock, *A vingança de Gaia*, vol. I. Editora intrínseca. Rio de Janeiro, 2006.

[3] K. Alam, T. Ray, S. G. Anavatti, "Design and construction of an autonomous underwater vehicle," *Neurocomputing*, vol. 142, pp. 16-29, 2014.

[4] R. B. Wynn, *et al.*, "Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience," *Marine Geology*, vol. 352, pp. 451-468, 2014.

[5] A. S. A. Gafurov, E. V. Klochkov, "Autonomous unmanned underwater vehicles development tendencies", Procedia Engineering, vol. 106, pp. 141-148, 2015.

[6] C. von Alt, "Autonomous Underwater Vehicles," *Woods Hole Oceanographic Institution*, 2003.

[7] W.E. Nodland, *et al.* SPURV II - "An unmanned, free-swimming, submersible developed for oceanographic research," *Oceans*, vol. 81, pp. 92-98, 1981.

[8] ISE, "Corporate profile: Remotely operated vehicles, autonomous underwater vehicles, hum an occupied vehicles and robotic system," International Submarine Engineering, Port Coquitlam, BC, Canada, 2015.

[9] V. Lucieer, N. A. et al., "Do marine substrates look and sound the same? Supervised classification of multibeam acoustic data using autonomous underwater vehicle images," *Estuarine, Coastal and Shelf Science*, vol. 117, pp. 94–106, 2013.

[10] H. Yuli, W. Jiajun, "Study on power generation and energy storage system of a Solar Powered Autonomous Underwater Vehicle (SAUV)," *Energy Procedia*, vol. 16, pp. 2049-2053, 2012.

[11] Solar-powered AUV: SAUV II [Online] Available at: http://auvac.org/uploads/platform_pdf/SAUVwhitePaper.pdf

[12] R. Stelzer, Autonomous Sailboat Navigation – Novel Algorithms and Experimental Demonstration, Tese de doutorado, De Montfort University, Leicester, 2012.

[13] J. C. Alves, N. A. Cruz, Fast – an autonomous sailing platform for oceanographic missions', IEEE, 2008.

[14] H. Erckens, *et al.*, 'Avalon – navigation strategy and trajectory following controller for an autonomous sailing vessel', IEEE, 2010.

[15] World Robotic Sailing Championship Available at: http://myisa.sailing.ie/

[16] B. Belcher, *Wind-vane Self-Steering: How to plan and make your own*, International Marine, 1982.

[17] Thrun, S. *et al.*, "Stanley: the robot that won the DARPA Grand Challenge, *Journal of Robotic Systems*," vol. 23, p. 661-692, 2006.

[18] C. P. Ochoa-Diaz, Estratégia de mapeamento em 2D de ambientes internos baseada na extração de segmentos de linhas usando sensores de ultrassom. Dissertação (Mestrado) - Dep. de Eng. Mecânica, UnB, Brasília, 2006.

[19] Pololu Dual VNH5019 Motor Driver Shield User's Guide [Online] Available at: https://www.pololu.com/docs/0J49.

[20] F. Plumet, *et al.*, "Toward an Autonomous Sailing Boat" *IEEE Journal of Oceanic Engineering*, vol. 40, pp. 397-407, 2015.

[21] X. Wang, *et al*,. "Reviews of power systems and environmental energy conversion for unmanned underwater vehicles," *Renewable and Sustainable Energy Reviews*, vol. 16, p. 1958-1970, 2012.

[22] *High Efficiency Multicrystal Photovoltaic Module*, Kyocera, Japan, 2015.

[23] *Solar Charge Controller XW-MPPT60-150,* Xantrex Technol., USA, 2013.

[24] Silva Junior, A. et al. Design and Implementation of a Control System for a Sailboat Robot. Robotics, v. 5, p. 5, 2016.