Design and Construction of the UFRJ Nautilus' 2018 AUV: BrHUE

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***Abstract*—The UFRJ Nautilus is a student-driven engineering project team at Federal University of Rio de Janeiro, focused on building and designing AUVs. The team is the first competitor in this field in Latin America, consisting of over 35 students from different courses. In this second year of competition, the team developed a new AUV called BrHUE, to compete in the 2018 AUSVI RoboSub Competition in San Diego, California. The robot is programmed to perform a mission without human interaction or any other remote operator, using artificial intelligence and image processing and recognition to complete the tasks.**

I. Introduction

UFRJ Nautilus team is a student engineering group of Federal University of Rio de Janeiro (UFRJ) focused on naval and submarine automation. Our undergraduate students designs, builds and programs an autonomous underwater vehicle (AUV) at low cost. The Nautilus AUV, called BrHUE, is programmed to perform a mission completely autonomously, without human interaction or any other remote operator. UFRJ Nautilus main goal is to compete, for the second time, on Robosub 2018, since it had participated before in the year 2016. The team is the first competitor in this field in Latin America, consisting of over 35 students from different backgrounds and courses.

The team was founded in 2016, by 8 undergraduate engineering students, as a way to motivate them to create high-end technology and to feel engaged with the Engineering course. Starting from scratch, the team dedicated themselves to building the best they can, with a few numbers of resources, since there was a difficulty in raising a big amount of sponsors and supporters in the beginning. Therefore, Robosub became the gateway for the group to start working on an innovative automation project, generating many positive results and new sponsorships (like IBM, Matlab, SolidWorks, and others). With the intention to keep innovating, robosub 2018 became a new opportunity to rebuild the robot and gain competitive advantages in a second participation. Nowadays, the robot can perform different tasks. The team offers a great academic and practical experience, combining research conducted in the classroom and a hands-on approach training, that is going to be better exposed in next chapters.

II. Competition Strategy

For RoboSub 2018, it is essential for UFRJ Nautilus to pass through the gate and go to semifinals since we didn't accomplish that in 2016. Besides that, doing the required task would engage ourselves in a continuous improvement of our project. Our strategies were developed based on Palouse team [1] and we are confident in passing through the gate and ready to make other tasks to try to get enough amount of points to go to finals.

We were preparing the BrHUE to do all the tasks of RoboSub 2018 competition, but the lack of resources forced us to retreat. We prepared all software necessary to locate the pinger during the tasks, this algorithm would locate the robot globally even on tasks not related to the pinger like buying a gold chip, but the hydrophones that we ordered through our sponsors didn't arrive in time. So, although we prepared the mechanicals system to buy a gold chip, roulette, and cash in tasks we are not focusing on that tasks anymore. We will try to sum many points we can on gate, path, play craps and play slots.

Thus, on gate task, we would pass from a random start, using the orientation provided by IMU, and we would adjust our BrHUE to the right direction and go forward until seeing the gate and then, using computer vision, the robot will pass through our called color to sum the maximum points. After, BrHUE might see the path with its bottom camera to follow it and reach the dices where the camera would identify the dices number 5 and 6 to sum 11, the maximum points. At the end, we would fire the torpedoes in the bottom slot without opening the others, because we don't see how BrHUE could open it in a safe way. During these tasks, we will ignore the dispensers as trying to accomplish it would be dangerous for the robot to lose its position.

It is remarkable that our strategy is simple but reliable and manages to do a considerable number of tasks with the high score so that we can play in the finals and semi-finals.

III. Design Creativity

A. *Hydrodynamics and Mechanics*

Since its first conception, the team's AUV project had a modular construction demand, due to several factors mainly related to difficulties in manufacturing and obtaining material resources and due to ease maintenance of the different parts and alterations in the arrangement.

Aligned to such needs and constraints, the AUV frame was designed from aluminium structural frames. These profiles can be easily assembled and disassembled into a structure that supports properly the attachments arrangement to be placed on the frame, as well as the arrangement of the propellers.

The electronic components for the processing of AUV actions need to be in a single main body, while the other electronic and autonomy components (sensors, cameras and batteries) can be in separate attachments, fixed along the

Fig. 1. CAD rendering of BrHUE.

frame. Thus, the team chose to use a centrifuged acrylic cylinder for the main body, dimensioned to contain the electronics inside and generate the necessary buoyancy and to guarantee positive floatage, as required by the competition rules.

The concern with acrylics structural resistance was also evaluated. The thickness was calculated to withstand a pressure of at least 2 atmospheres, due to the depth that the AUV can reach during the execution of the test, but we oversize to withstand a pressure of up to 10 atmospheres, aiming at the possibility of performing tasks in greater depths. A cylinder of 270 x 500 mm and 5 mm thickness was reached. For the design of the annexes, the same concerns will be considered.

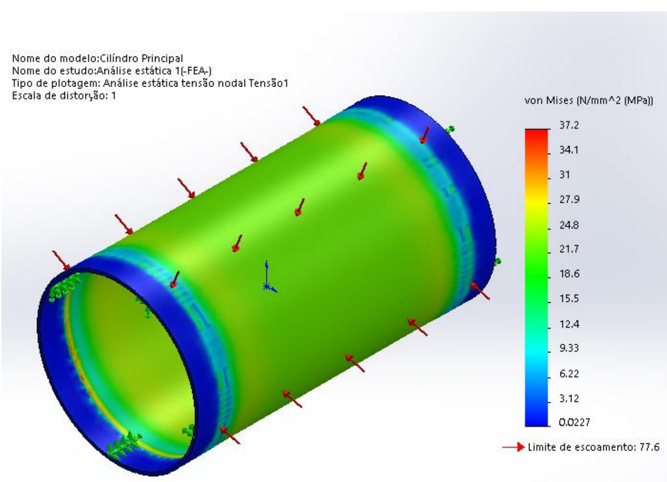

Fig. 2. Von Mises stress result from pressure static analysis of the acrylic main body.

The design of the hatch covers was developed mainly for obtain efficient covers that allow access to the electronics inside and at the same time, guarantee the perfect tightness of the AUV when submerged through the appropriate O-rings.

We created a modular system of movable cover coupled to a drawer, which main function is to support and organize the AUV electronic part, besides allowing access to each board of electronics independently. The proposed internal profile is made of circular vertical plates, which give the possibility of coupling the electronic boards. These plates remain cohesive through four horizontal rods, which, secured to the movable cover, provide joint movement by pulling the cover.

Fig. 3. Exploded view of BrHUE AUV.

The propulsive system has always been a project in which team tried to develop technically. In addition, since 2017 we have sought to develop a propeller designed entirely for our AUV and that competed on a professional level with commercial propellants.

Our first definition it is related to the motor. The teams from Hydromechanics and Electronics verified that the best option as a motor for the AUV would be the Multistar Elite 3508 - 268kV High Voltage Endurance Motor, considering not only technical but also economic issues. The decision to define a motor facilitated the design of the propulsive system since it was not necessary to investigate several possible motor-propeller combinations. All that was needed was a to find for a propeller that would work for the AUV's operational profile and consider the characteristics of the rotation and torque.

The next step was to define what kind of series to use as a propeller. There are several systematic series of predefined propellers that make it easier for the designer to find the best pitch, rotation, diameter and propeller area ratio configuration that could be compatible with the technical characteristics of the motor already defined. The definition of the type of series should consider the operational profile of AUV. After intense research in the literature [2] and consulting specialized professors, Ka4-70 series with a Nozzle 19a pipe was chosen. The reasons why we opt for this model were basically two: the AUV operating speeds are low, and it was a good choice to use a pipeline that accelerates the flow to the propeller and increase its efficiency; and, second, the thrust generated by each propeller were similar, regardless of the direction of rotation of the propeller.

With the series defined, we began to investigate which technical characteristics of a propeller (diameter, pitch, area ratio and rotation) would be reasonable for the range of rotation and torque allowed by the motor. For all systematic series, we find in the literature interpolating polynomials in which the variables are the technical characteristics and the result is thrust and torque (or KT and KQ) for each configuration. This tool was used to find out which configurations were compatible with the motor and which ensured greater propeller efficiency. Defined the best propeller configurations, the pipe was designed based on them. In fact, the only parameter of the pipe is the diameter, already defined for the propeller, since the profile is defined by its type (19a).

Fig. 4. Customized thruster design: propeller and pipe.

With all characteristics and points that defined all the profiles of the propeller and pipe defined, the team used SolidWorks software for modeling. Some adjustments had to be made: for example, at the leading edge and leakage of the propeller blades, for the thickness do not get so small and manufacturing process unfeasible. Therefore, the manufacturing process chosen was the 3D printing, for technical and economic reasons. This process of printing and adjusting the modeling in the software was done in several steps until the result was considered satisfactory.

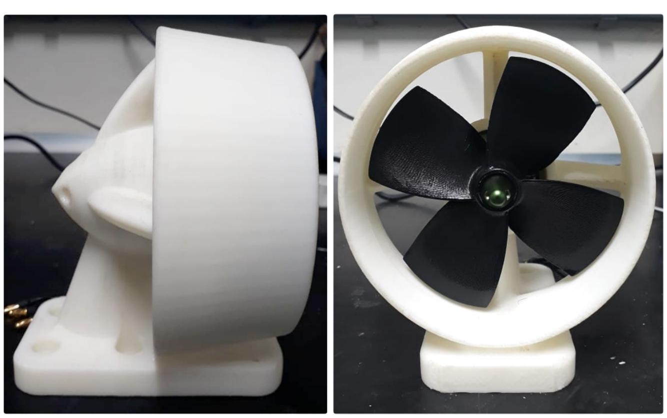

Fig. 5. 3D printed customized thruster.

B. Electrical

Electrical and Electronics Design was made to optimize the relation between quality and low cost. Primary goal for this years competition was to minimize loose cables or mechanical failures, and to have a great thermal consistency.

1) Motor Board: Motor Board was designed to withstand current measurement without temperature variation. The main goal was to create a feedback loop of each motor power consumption and also to have reliable connections. Six 30amps OPTO AfroESCs that drive our custom made propellers are controlled by a Teensy 3.2.

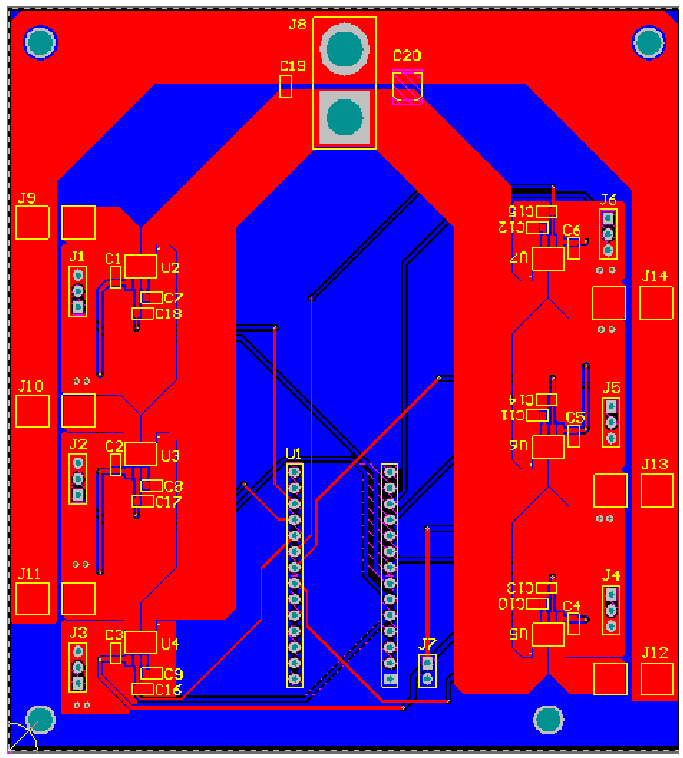

Fig. 6. Motor Board.

2) Motherboard: Our Industrial Mini-ITX Motherboard is powered up by a 450W PSU capable of driving enough power to our processing efforts using a Intel Core i7 along with 16GB of DDR3 Memory.

3) Sensor Board: To monitor some internal conditions of the main hull we developed board that contains 4 leak sensor and 2 Temperature and Humidity Sensor for redundancy.

4) Battery Management System: The BMS used is a PCM HCX-D596 / 214AF capable of handling our 2x 8000mAh 6S 30C LiPo Packs. Each pack uses a BMS that can support currents up to 90 Amps.

5) Navigation: Our AUV uses an also industrial pressure transducer capable with an experimental resolution of 0.1cm when used with a 16-bit ADC. We also use the Xsens MTi-30 AHRS for orientation.

6) Cameras: We are using two OpenRov HD camera at this time.

C. Software

At our first time in 2016 software development was not the main concern of our team. But with the experience of that year's competition we started to structure and increase software members. And through these years many people pass through this area making a consistent development. This fact has not stopped us and now software area has a total of 9 members divided in: Ecolocalization, Movement Control, Computer Vision, Artificial Intelligence and Simulation (we will talk about the simulator in experimental results section).

For this year, the software division was concerned about creating a reliable system, and to have a fast development we use ROS to manage all robots application, OpenCV to computer vision and MATLAB to fast tests of algorithms exporting to C++ code. We do not have preferences on programming languages or frameworks, we just use what would be easier, faster and better documented tool.

1) Ecolocalization: Ecolocalization was our best developed system, the goal it is to find the pinger's Azimuth and Elevation about our AUV, this measurements with depth sensor allow us to have the localization of BrHUE during the tasks. This system has been idealized and implemented for 1.5 years, the last 10 month with Navy Research Institute of Brazil (IPqM) assistance.

We developed an implementation of Beanforming algorithm on MATLAB, which considering the arrangement of hydrophones it finds best signal delay that synchronizes all hydrophones, and then with some calculations it converts this time delay for each hydrophone into global Azimuth and Elevation. On Figure 11 it's possible to see the best fit region of these time delay. One disadvantage of this method it is that each hydrophone has to be in a close distance of each other due to high frequency, small wave length.

2) Computer Vision: The goal of our computer vision system it is just to get the pose of the objects, this mean that we capture 3D translation and 3D rotation of the object. Besides that the vision system has also to tell states machines if the objects seeing on camera match with expected observations, identifying the number of each dices too. To accomplish that, all computer vision system were developed in OpenCV, both python and C++ considering mono vision system. One requisite to our computer vision system to work it is have prior measurements of each object desired to get the pose during the tasks.

Our code just have to segment each image to isolate the desired object, and then we have to catch some specifics points in the image that it is known it's position on object's plane (that we created using it's specification). After that, with our cameras calibrated, we just have to solve a matrix equation [3] to find object's pose, and fortunately OpenCV has a built-in method for that. Figure 10 show it, we segment Roulette colors, see the position of each piece and put them together to get it's pose.

One interesting trick on our vision system it's about the dices recognition. It was easy to find some codes that segment the dice and assume that the number of black points on desired face it's the dice number. But that codes was not reliable because we saw that if noises make camera see one more or one less black point we would make wrong assumption. To covers that, we verify if the geometry of the black points it is consistent with our prior assumption of number of black points. This was possible because each dices number have specific arrangement and we will never see a number 6 face with 5 black points and say that was a 5 face, although we can't differentiate small numbers much effective.

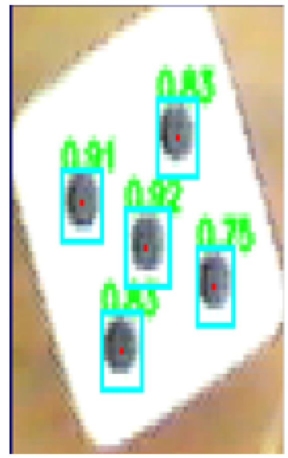

Fig. 7. Dice detector, segmenting each black point to take it's geometry.

3) Artificial Intelligence: The goal of our artificial intelligence (AI), it is to plan every movement of our AUV and control the events during a run. Our AI was based on Palouse team development, so we developed it in Python using Smach on ROS. Smach it's a framework on ROS that let us to develop high level states machines. Consequently, our AI it is based on a decision tree fully mapped, so we implement it with Smach and BrHUE will follow our previous decisions.

We had to adapt some project's decisions to our BrHUE, including some refined states machines to let us scores more points during the run. As our robot it's different, has other limitations and our computer vision system it is completely different ecolocalization system. So we had to adapt many thingS and chance many details to make the main idea run on our AUV.

4) Movement Control: AI it is responsible to high level decisions, but control system that has to make the AUV reach the desired point, so, on our architecture IA send to movement control want the robot must do and then control system has to make the AUV do it actuating on thrusters. We used PID controller because it appeared to be the best deal of complexity and reliability.

We started to implement our version of PID controller to our BrHUE, but since we found the Palouse implementation, which was very modular and parametrized, we just studied it and fill the code with BrHUE parameters and everything worked as shown in Figure 9.

IV. Experimental Results

To validate all the software and our project design we developed a simulator of RoboSub 2018 competition on Gazebo7, using as base the world created by Palouse team and available online on GitHub [1]. We modeled all new objects that will be on competition, and with that integrated on ROS we were able to get performance feedback of all vision codes, artificial intelligence and movement control.

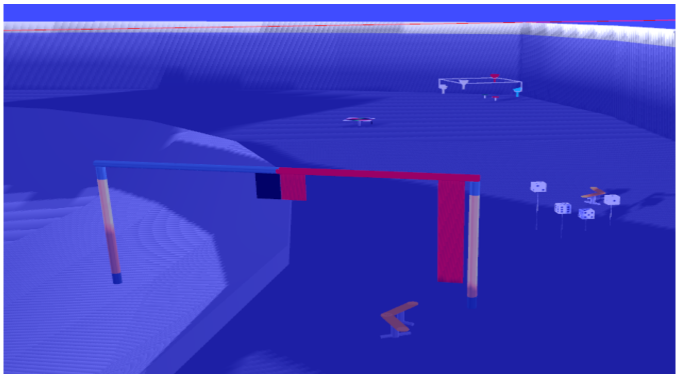

Fig. 8. RoboSub 2018 modeled on Gazebo7 simulator.

The simulator showed us many important things. Testing our control on simulator we noticed that the thruster arrangement chosen by us could make the BrHUE drift laterally, although rotate the sub easier. To fix that, it's important to the AUV get constantly its relative pose to objects, so if the drift occurs, the error must be corrected automatically by the controllers.

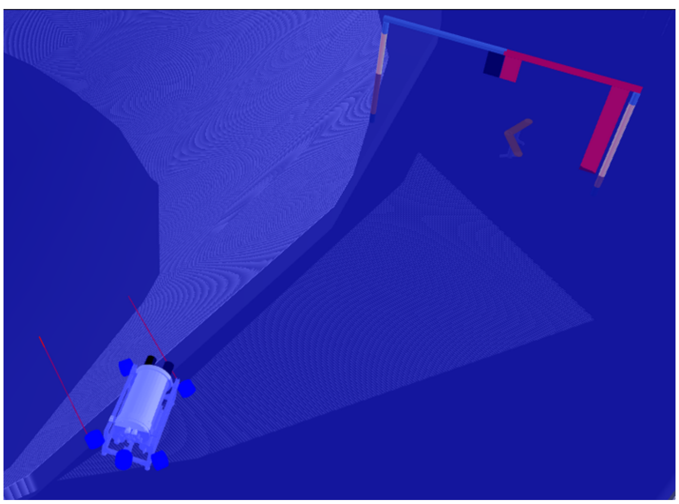

Fig. 9. BrHUE modeled on Gazebo7 simulator, actuation represented by red lines.

Our computer vision codes were developed before the simulator. Thus, we measure its performance outside the water and on a simulator. We were able to see all the 6D pose captured by our camera, and measure its error which was in a range of 5% (Figure 10).

All of our pinger localization algorithm was developed and simulated in MATLAB. On our code, we were able to put some physical arrangement of hydrophones and see the region of a high probability of having the pinger. Consequently, we could identify which hydrophone would fit or not, since we discovered that the distance between them must be very small, forcing the hydrophone to be tiny.

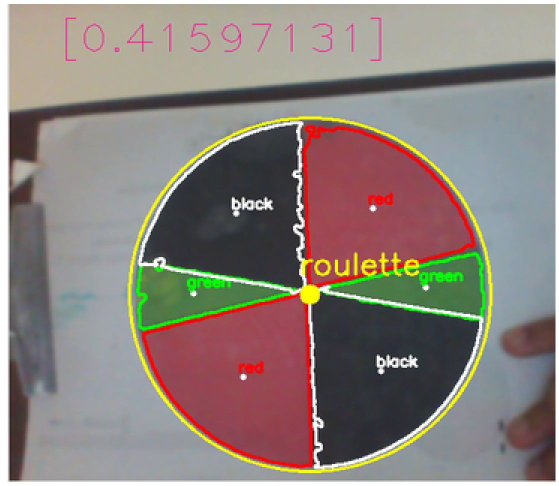

Fig. 10. Roulette identification, on top the total distance between camera and roulette.

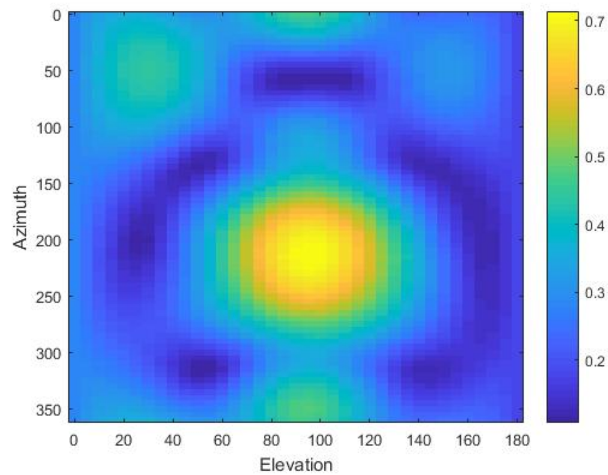

Fig. 11. Simulation with pinger at 211 Azimuth and 95 Elevation

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APPENDIX A

	Component	Vendor	Model/ Type	Specs	Cost (if new)
Frame	aluminum profile	Forseti - Perfil Estrutural em Alumínio		30x30cm Basic; 30x60cm	$ 67.00
Waterproof Connections	connectors	SEA-CON/Brantner & Associates, Inc.			$ 2,910.00
Thrusters	Multistar Elite	Hobbyking	3508-268KV High Voltage Endurance Motor		$ 259.72
Motor Control	Afro 20A Muti-Rotor	Hobbyking	ESC OPTO (SimonK Firmware)		$ 72.00
High Level Control	Custom	-	-	-	-
Actuators	Custom	-	-	-	-
Propellers	Custom	-	-	-	-
CPU	Mini ITX	Cortex	XEB-8670-ML00AT2L		$ 500.00
Internal Comm Network	USB	-	-	-	-
External Comm Network	Ethernet	-	-	-	-
Inertial Measurment Unit (IMU)	MTi-30-AHRS-2A8G4	Xsens			$ 1,400.00
Camera(s)	Pro Camera-HD Upgrade	OpenRov			$ 700.00
Hydrophones	Bii- 7141	Benthowave			$ 1,200.00
Team size (number of people)	29	-	-	-	-

Fig. 12. Table