Improvement of the UFRJ Nautilus' 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 to compete in the AUSVI RoboSub Competition. For the team's 3th season competing in competition, the team reviewed it's second AUV called BrHUE rebuilding all the internal hardware, re-projecting it's software and changing it's propellers. The priority of the team was deliver a robot capable of localizing it self on the pool, with more reliability from all hardware and mechanical systems.**

I. Introduction

UFRJ Nautilus team is a student engineering group of Federal University of Rio de Janeiro (UFRJ) focused on autonomous vehicles. Currently, the unique project developed by the team is the Autonomous Underwater Vehicle (AUV) for AUVSI Robosub Competition. Our undergraduate students design, build and program an AUV to have the lowest cost as possible, as the team have to get sponsors by themselves, making all the work harder. The Nautilus' AUV, called BrHUE, is programmed to perform a mission completely autonomous, without human interaction or any other remote operator. UFRJ Nautilus' main goal is to have an intelligent AUV capable to localize itself on TRANSDEC, and based on that the team expect to sum enough points to rank to the finals. The team is the unique Robosub competitor in Latin America, consisting of over 35 students from different backgrounds and majors.

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 major. Starting from scratch, the team dedicated themselves to building the best they can, with their own resources. With the intention to keep innovating, the team had grown and started the new AUV, called BrHUE. To compete in 2018, the team made a crowdfunding to afford part of the trip costs and acquired enough sponsors to build the BrHUE. Due to team efforts to make an reliable AUV and the use of software simulations, UFRJ Nautilus could classify to semi-finals without having pool testing in Brazil as some sponsors delayed to deliver some equipment's. At the end of Robosub 2018, water came into our AUV and we lost our entire hardware, so we made a raffle to fund the project and we redesigned all our hardware.

II. Competition Strategy

For RoboSub 2019, it is essential for UFRJ Nautilus to accomplish all the tasks that just need robot movement: Gate, Slay Vampire and Expose to Sunlight. These tasks just need our localization system working and control system to drive robot to desired place. The team prioritizes the robustness of it software without throwing away complexity, this comes in their project with many levels of complexity in their software and the team decide which of them they would like to use according to previous performance and sensor readings. So, the most complex software has more chance to not work and the simplest one doesn't perform the best as possible, therefore UFRJ Nautilus choose to try both.

The decision to maintain the same AUV from 2018 to 2019 came from the possibility of having more testing time to extract the best performance from our software. Since we lost our entire hardware in the flooding accident during last edition, the first logical solution was to start the project from scratch. However, we didn't have enough resources to do so. So, coming back from Robosub 2018 team recruited new members and made a Christmas raffle to afford this repairs. With the lack of time in mind, we had to ignore the manipulation tests were ignored, but the team expect to sum the most points possible without manipulation.

The first problem we've faced was the incompatibility of the new CPU/GPU system with the Data Acquisition Board of the Acoustics System. And without tracking the pinger position it's possible that BrHUE won't find the Expose to Sunlight task. But if our localization system is robust enough to emerge on Expose to Sunlight task after passing through the gate and slaying vampire we hope that it is capable to rank to the finals.

Fig. 1. CAD rendering of BrHUE.

III. Vehicle Design

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 easy maintenance of the different parts and modifications in the arrangement.

With such need and constrains in mind, 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.

Different from 2018 the team decided to put all the hardware together, except the battery that it is on a separated annex. This change it's to minimize the volume of the robot, organizing better the hardware displacement. 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 annex, the same concerns were considered.

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.

UFRJ Nautilus hydrodynamics and mechanics' team had reviewed the 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. In 2018, the proposed internal profile was made of circular vertical plates, but all the hardware boards are rectangular. So, they decided to put horizontal plates where the thinners board are placed closer to the acrylic curve. These plates remain cohesive through four horizontal rods, which, secured to the movable cover, provide joint movement by pulling the cover.

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 was able to compete on a professional level with commercial propellants. In the beginning it worked fine, however the structure of the motor that powered our thruster was built in a corrosive material, so it didn't last enough time to be viable. So, the team preferred to buy the entire thruster from Blue Robotics because on the previous propeller the project parameters was never validated if it matches the real ones. So the idea is to learn how to measure the real parameters from the Blue Robotics' thrusters to after redesign our propellers using Blue Robotics' waterproof motor and validate it. In addition, the team had to design a 3D printed fitting part to adapt the new propellers to our structure.

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 the amount of volume required by all the hardware, this was the first lesson learned at Robosub 2018 as the total volume of BrHUE were too big and we had to add a lot of weight on it.

Due to water flooding in BrHUE at the end of competition in 2018, a system was made to detect water inside the AUV to shutdown all the power as a damage control action.

So all hardware system was redesigned, the unique sensor that remains the same it is the IMU. The new eletrical project design are shown at the Figure 2. The challenge of this area is to interface well the software requirements with the physical aspects of the BrHUE, and to do so the UFRJ Nautilus electrical team had to concern about temperature, current, interference between the boards, protection and monitoring systems. Some systems and boards of BrHUE:

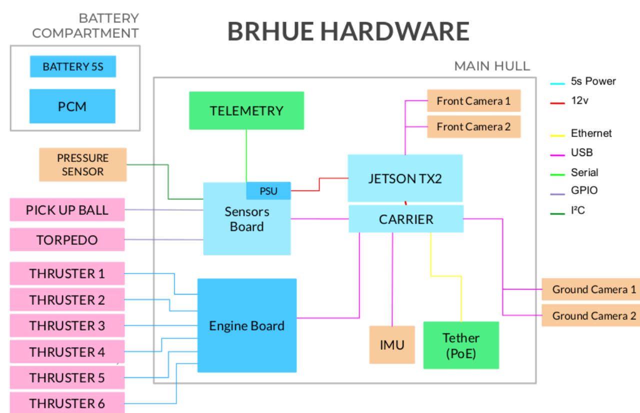

Fig. 2. Diagram of the new electrical design.

1) Motor Board: Motor Board was designed by UFRJ Nautilus to withstand current measurement, a software requirement, without temperature variation. The main goal was to create a feedback loop of each motor power consumption and also to have reliable connections. The difficulty of that board was to support all the current required to power the 6 thrusters and to have a precision measurement of these currents. The battery, six ESC's, and a Teensy 3.2 are attached to this board. The Teensy is responsible to control the ESC's. The motor board is shown at figure 3.

2) Motherboard: In 2018 the mother board used by the team was a mini-ATX with an Intel i7, this board had a high power consumption (450W) requiring another boards to supply this power and and over-heating. Therefore, we've changed to a Jetson TX2 board, which attends new software requirements as deep learning and faster image processing due to it's GPU. with this new board, the power consumption was drastically reduced as well as the board volume and PSU system.

3) Sensor Board: The sensor board was designed by UFRJ Nautilus and it's also an important part of our hardware system, because it holds together all our tiny sensors that are measuring temperature, humidity, the internal pressure and external pressure (depth). A Teensy is attached to this board to receive all the information and pass to the computer and to a display that it is a supervisor system when we are testing the AUV. The sensor board is shown at figure 4.

4) Battery Management System: The Battery Management System (BMS) is a board that monitor each cells of the battery

Fig. 3. Motor Board.

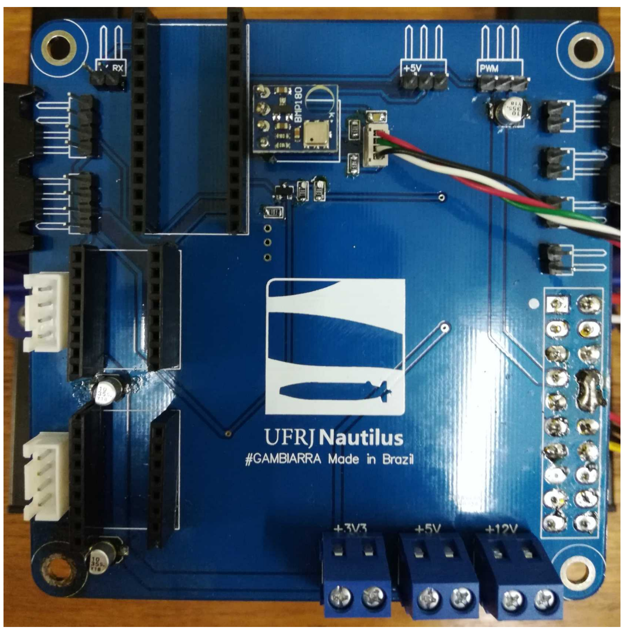

Fig. 4. Sensor Board.

and maintain each cell with the same voltage keeping the battery stable. In addition to BMS, the internal pressure of the battery annex and the temperature are monitored, by a system developed by the team, and if something gets wrong the battery is turned off.

C. Kill Switch

The kill switch of UFRJ Nautilus it is a magnetic key, so the team designed it to don't make any extra hole to receive the kill switch. A 3D printed with a magnetic piece goes outside and inside we have an magnetic sensor that opens and closes the circuit in the presence of the magnetic piece. This sensor is connected with motor board, cutting the power to the motors and informing the Teensy and so the computer that the motors was shut down. The kill switch are shown at Figure 5.

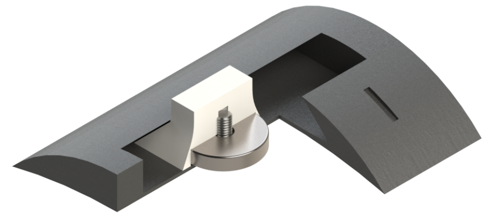

Fig. 5. Kill Switch

D. Hydrophones Board

UFRJ Nautilus developed an filter board for the hydrophones, so just the desired frequency of the filter are passed to the data acquisition board. This were required by the software team to allow them to sub-sampling the signal, requiring a data acquisition board with less rate of sampling making it cheaper and affordable to UFRJ Nautilus.

E. Software

Since the conception for Robosub 2018, our software design was totally based on [1] team, their software was totally available on Github and well documented. That repository taught many things to UFRJ Nautilus, and on that year the control system and simulation interface were the same on both teams. But for Robosub 2019, UFRJ Nautilus has not used new developments from Palouse team and has modified more the software systems.

After Robosub 2018 we have noticed that software division has more to do on site than other areas, because during the competition we usually have to make improvements. Other thing that was noticed at the competition was the importance of a Positioning System, the robot has many sensors that give information about relative position about something and getting this information together to make a real Positioning System is crucial.

UFRJ Nautilus increased the amount of software members to 11 that are divided in: Ecolocalization, Movement Control, Computer Vision, Artificial Intelligence, Positioning System and Simulation (we will talk about the simulator in experimental results section).

For this year, the software division was concerned about the Positing System creating a reliable system, that should work without some sensors and have levels of complexity. To have a fast development we used Robot Operating System (ROS) to manage all robots application, OpenCV to computer vision and MATLAB to fast create and test new algorithms. 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 is to find the pinger's Azimuth and Elevation from our AUV, this measurements with depth sensor allow us to have the position of BrHUE relative to the pinger. This system has been idealized and implemented for 1.5 years [2], the last 10 month with Navy Research Institute of Brazil (IPqM) assistance.

We developed an implementation of Beamforming 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. The results we discuss at experimental results section.

The IPqM sponsored UFRJ Nautilus with the donation of 4 hydrophones and a data acquisition board with 500kS/s/ch that acquires the signal synchronously. Unfortunately, changing our motherboard to Jetson TX2 made the data acquisiton board incompatible with the software. But with that trouble we tested at IPqM the result of our algorithm with lower sampling rate by interpolating the signal considering the prior frequency of the pinger. Knowing the frequency the aliasing problem don't occurs and then we use the interpolated signal as input to our algorithm and it worked well.

2) Computer Vision: UFRJ Nautilus' computer vision systems were completely remade, after Robosub 2018 the team started to use stereo vision. Two goals were defined in the beginning of the new computer vision design: Capture the 6D pose of the objects and do visual odometry.

The computer vision division was split in this goals, and after some research, we have observed that the techniques to solve both problems were basically the same. Both involves techniques to find features on the image and match these features between the cameras (to capture the pose) or between the time (to do visual odometry). So, the team decided to use a well known algorithm of visual simultaneous localization and mapping (SLAM), that has an implementation on ROS of ORB-SLAM2 [3]. The team tried to not use this SLAM algorithm because it generates more information than needed, but use an unique ready code showed better than use two different codes that do the same operations.

Besides that, an alternative to capture the 3D translation pose of an object was the bounding box provided by a neural network with the advantage of identifying the object. This is an approach similar to what UFRJ Nautilus had in 2018 but changing the color segmentation to a neural network. The team tested the neural network and the use of deep learning became a second possible solution since with the ORB-SLAM2 it is possible to manually tell the robot where each object is on the map made by ORB-SLAM2 and after running it just using localization without mapping.

3) Positioning System: UFRJ Nautilus' positioning system, also called localization system, is the main innovation of the team for Robosub 2019. In 2018, the team observed that if the AUV maintain it's position in TRANSDEC during the tasks and if it knows the position of each object in TRANSDEC, the AUV just need to navigate to perform each task. So, the key to have success on Robosub it's to use every sensor readings to catch an information of global position. The team had studied many methods [4] to track the global position of the robot, since Monte Carlo Localization is a commonly used method for global localization, we thought using it was a good choice,

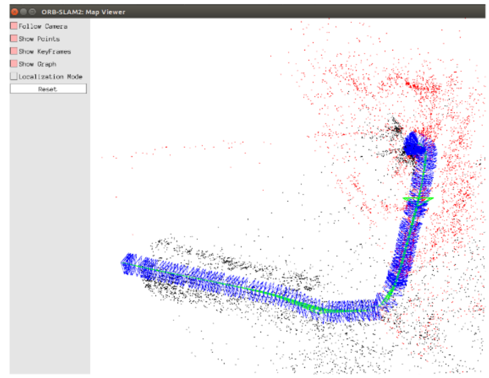

Fig. 6. Map generated by SLAM.

but the final option chosen by the team was Kalman Filter. Although Kalman Filter doesn't solve the global localization problem, it's much used to track the local position. So, since the AUVs at Robosub always start from almost the same point, Kalman Filter can be used considering the initial position as zero coordinate and then keep tracking of it's position means knowing the AUV's global position on TRANSDEC. Of course the objects' position at TRANSDEC are also refered to AUV's initial position, the zero coordinate.

Using the Kalman Filter [5] turns the developmnet easier, since it has many open source implementation and online documentation. So, this algorithm make the sensor fusion, receiving all sensor movements reading like visual odometry, position relative to pinger and acceleration reading from IMU. As a choice of UFRJ Nautilus, the Kalman Filter should infer just the 2D translation postition. It was considered the depth as perfect reading by the depth sensor and also the orientation given by the IMU.

To take the most of this system, as UFRJ Nautilus can't afford a Doppler Velocity Log (DVL), the team decided to take the most of the acceleration reading of the IMU. So, the team made a separated filter to acceleration in many levels [6], first in the raw data to try to eliminate some noises, then this acceleration are integrated once giving velocity. To velocity we apply the same filters but with different constraint, and then this signal are integrated once giving the movement of the AUV. To achieve this result many different methods were tested but this gave us better results. At Experimental Results section this results are better discussed.

4) 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 [1] development, so we developed it in Python using Smach on ROS. Smach is 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.

For Robosub 2019 the team decided to create many complexity levels of state machines that are redundant. This idea came from a trouble that UFRJ Nautilus suffered at Robosub 2018, when the cameras didn't work, so at that time the state machines were completely dependent on the vision system and to pass through the gate the AUV received the commands manually. Now the team had develop 2 entire state machines, the simpler one considers just the IMU and depth sensor and other considers positioning system working that uses computer vision (cameras), echo-localization and the IMU.

It is important to remember that the localization system just need one of their inputs to work. So, the more complex one sends commands to the control system to drive the robot to certain position on the map and then the AUV start to execute a sequence of movements to global positions that perform the task. This sequence of movements is necessary to stabilize the error of localization system with the sensor readings at each moment. The simpler one is a sequence of defined movements from the deck, it sets the robot in a desired angle and depth, and than the robot moves blindly ahead maintaining these constraint during a specific time. So, with this simpler state machines any collision during the tasks means the end of the run because no feedback from the world is being considered.

Besides that machines, this division it is also implementing two other sets of machines states that are similar with those from robosub 2018. These machines don‘t use the localization system, but uses vision to do a bounding box on desired object and getting relative pose to them. One set is exactly what the team had in 2018 using color segmentation and other uses deep learning to identify the objects instead of color segmentation.

5) Movement Control: AI is responsible to high level decisions, but control system that has to make the AUV reach the desired point, so, on our architecture AI 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.

After Robosub 2018 the team started working on control system decided to find the real parameters from our thrusters to infer the thrust given by each one, measuring just the current on each motor to make a cascade controller. This idea worked on Simulink implementation using Kalman Filter, but find those real parameters it was a thought mission. So, all technical and management areas decided to buy the Blue Robotics thrusters. With the curves of the thrusters of Blue Robotics, the control team saw that the transient response of the thrust from the thrusters were too fast so the cascade controller became useless.

After that, we improved some behaviors on the transform between the resultant 6D force vector given by the PID controller and the power given to each thruster, like the saturation that just limited the power to the motors making the resultant force vector to point to another direction although the absolute value remained the greater possible. The team decided to change it to preserve the direction of the vector consequently decreasing the absolute value of it. Other improvement manner of its conversion, before it was considering a linear transform, so if the maximum thrust was 30N with maximum power to achieve 15N it was set half the maximum power. The team took the Blue Robotics curve of thrust and interpolated it so now the control system have a nonlinear function that maps the desired thrust on each motor to PWM signal (power) applied.

This team also improves the PID control with one more operation of movement, that moves the robot using relative position of the robot at that moment. Before the controller developed by Palouse just move the AUV considering global reference of the map. So, if the robot see a buoy that want to get in, the robot should just move further. But this was impossible, the robot had to get the absolute pose of the buoy to drive to it or drive blind forward to touch it. Now our controller is capable to just send our robot a meter forward, making this control interface with AI team easier.

IV. Experimental Results

The main experimental results that the team consider the innovation for RoboSub 2019 are shown on this section: IMU integration and Echo-localization tests.

A. *IMU integration test*

As mentioned before, we integrate the filtered acceleration to obtain position. The tests, at first consisted in going 1 meter in a straight line, then a circular path were tested. However, the first test did not evaluate the sensors capability of detecting a closed path, i.e., returning to the origin, while in the latter, it became difficult to measure distances and the movement direction compared to the expected measurements. Therefore, the team opted for a closed linear path testing each axis of direction at a time, a square path.

The results were experienced mixed with the IMU and the filtering methods after testing. Depending of the acceleration input, the filters would give either a reliable acceleration output to integrate or not.

The Figure 7 shows the raw data, mean and sync filter for each X and Y axis during the square movements. At each vertex of the square a pause was made, as shown by 0 readings. At 8 it is possible to clearly observe the square movement, at each pause on square vertex the filters delayed to converge. This is due to filter response of phase that delays the signal. But, fortunately after a while it converges.

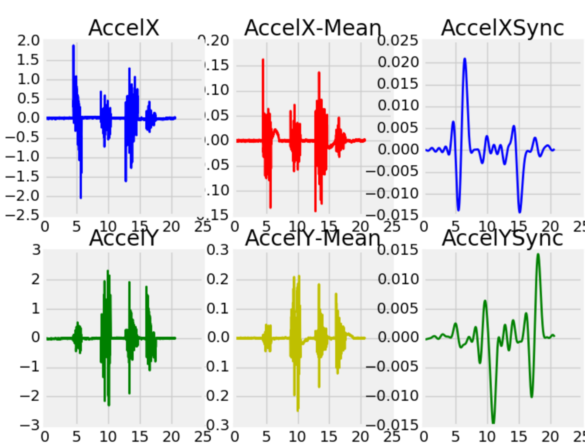

Fig. 7. Sensor readings at each X and Y axis.

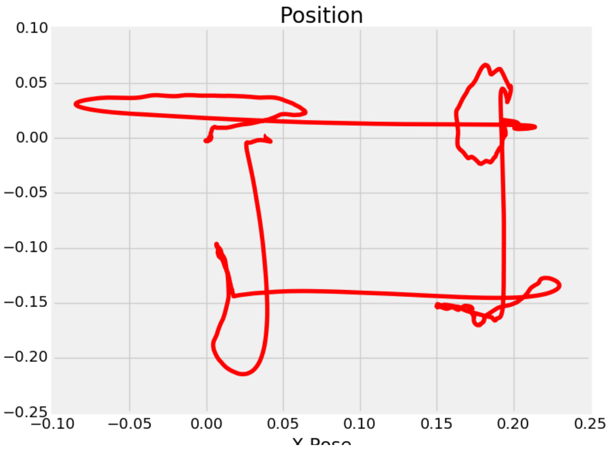

Fig. 8. Square trajectory made by the IMU.

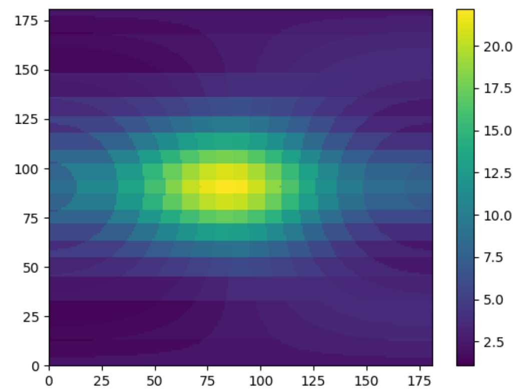

Fig. 9. Azimuth x Elevation Time domain Beamforming graph. The pinger and hydrophones have a 90 degree azimuth and elevation angle. The colors represent the squared mean for each point. The point with the bigger mean is our (azimuth, elevation). This algorithm returns that he angles are in the range of 83 and 97 degrees for both angles.

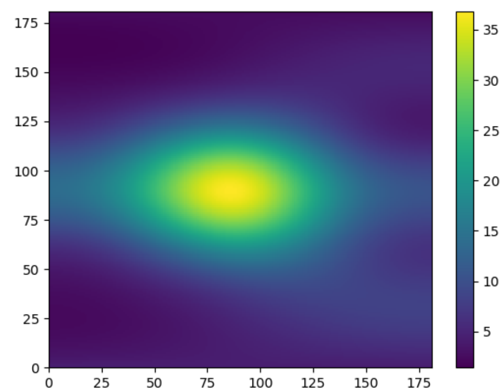

Fig. 10. Azimuth x Elevation Time domain Beamforming graph. The signals used were the same from figure 1. We see a bigger resolution and the algorithm returns that the (azimuth, elevation) pair is (91,85) degrees.

B. Echo-localization test

Two different sets of tests were made in conjunction with IPqM. The first ,was done for RoboSub 2018, to verify that the algorithm indeed works. The pinger frequency was set to 19.2kHz and the signal was captured by four hydrophones displayed in a T-shaped orientation, to measure the azimuth angle between the hydrophones. The second test was done trying to emulate the possible signals which would be used at RoboSub, that is sine pulses of 40ms every two seconds and frequencies of 25kHz, 30kHz, 35kHz, 40kHz. The hydrophones configuration was also altered, with one hydrophone on the x axis, one on the y axis and two on the z axis, to be able to measure the relative azimuth and elevation between the pinger and hydrophones.

The Beamforming algorithm on the time domain proved not to be as accurate as necessary, as it did not have enough resolution to distinguish between nearby angles (angles within +- 10 degrees) as shown in figure 9. The frequency domain tests proved more accurate, managing to detect differences of 1 degree of both elevation and azimuth between the pinger and hydrophones, as shown at figure 10.

As the angles between the pinger and hydrophones approach 0 or 180 degrees an accuracy loss was detected. This is, in part, due to the given configuration as well as the Beamforming algorithm limitations. For angles between 30 and 150 degrees Beamforming proved to work as intended, managing to identify the angles between the pinger and hydrophones with +- 5 degrees of uncertainty.

Acknowledgment

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Appendix A

Below it has a table where we show our team's expected point comparing with the points that we really did.

Subjective Measures			
	Maximum Points	Expected Points	Points Scored
Utility of team website	50	35	
Technical Merit (from journal paper)	150	120	
Written Style (from journal paper)	50	40	
Capability for Autonomous Behavior (static judging)	100	65	
Creativity in System Design (static judging)	100	80	
Team Uniform (static judging)	10	8.5	
Team Video	50	45	
Pre-Qualifying Video	100	0	
Discretionary points (static judging)	40	20	
Total	650	413.5	
Performance Measures			
	Maximum Points		
Weight	See Table 1 / Vehicle	50	
Marker/Torpedo over weight or size by <10%	minus 500 / marker		
Gate: Pass through	100	100	
Gate: Maintain fixed heading	150	150	
Gate: Coin Flip	300	300	
Gate: Pass through 60% section	200		
Gate: Pass through 40% section	400	400	
Gate: Style	+100 (8x max)	400	
Collect Pickup: Crucifix, Garlic	400 / object		
Follow the "Path" (2 total)	100 / segment	100	
Slay Vampires: Any, Called	300, 600	600	
Drop Garlic: Open, Closed	700, 1000 / marker (2 + pickup)	700	
Drop Garlic: Move Arm	400		
Stake through Heart: Open Oval, Cover Oval, Sm Heart	800, 1000, 1200 / torpedo (max 2)	800	
Stake through Heart: Move lever	400		
Stake through Heart: Bonus - Cover Oval, Sm Heart	500		
Expose to Sunlight: Surface in Area	1000		
Expose to Sunlight: Surface with object	400 / object		
Expose to Sunlight: Open coffin	400		
Expose to Sunlight: Drop Pickup	200 / object (Crucifix only)		
Random Pinger first task	500	500	
Random Pinger second task	1500	1500	
Inter-vehicle Communication	1000		
Finish the mission with T minutes (whole + factional)	Tx100		

Fig. 11. Table

APPENDIX B

Below it has a table where we show our team's list of components.

Component	Vendor	Model/Type	Specs	Cost/If new
Frame	Forseti	Aluminum Profile	-	-
WaterProof Connections	Seacon	IL4MP/IL6MP/IL8MP/IL16MP	-	-
Thrusters	BlueRobotics	T200	16V KgF	169.00
Motor Control	BlueRobotics	BasicESC	R3 30A	22.50
High Level Control	-	-	-	-
Actuators	Custom	-	-	-
Propeller	BlueRobotics	T200 Propeller	-	-
Battery	MaxAmps	22000mah 5S LiPo Battery	-	-
Converter	-	-	-	-
Regulator	-	-	-	-
CPU/GPU	NVIDIA	Jetosn Tegra X2	-	-
Internal Comm Network	-	USB/I2C/TTL SERIAL	-	-
External Comm interface	-	ETHERNET	-	-
Programming Language 1	-	C++	-	-
Programming Language 2	-	Python	-	-
Comapss	-	-	-	-
Inertial Measurement Unit	Xsenses	MTi-3-AHRS	-	-
Cameras	Logitech C920		-	-
Hydrophones	Benthowave	Bii-7141	-	-
Manipulator	Custom	-	-	-
Algorithms: vision			-	-
Algorithms: acoustics			-	-
Algorithms: localization and mapping			-	-
Algorithms: autonomy			-	-
Testing Time: Simulation	200h			
Testing Time: In Water				
Team Size	9 in RoboSub - 30 Total team			

Fig. 12. Table