Development of an Autonomous Underwater Vehicle for the International RoboSub Competition

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***Abstract*—The ASDL Marine Robotics Group is competing for the second time in the International RoboSub Competition. Lessons learned at last year competition are used to make improvements to the baseline vehicle.**

I. INTRODUCTION

The Georgia Tech Marine Robotics Group is part of the Aerospace Systems Design Lab (ASDL) at the Georgia Institute of Technology in Atlanta. The team is competing for the second time in the International RoboSub competition. In 2016 the team qualified for the semi-finals.

This year the RoboSub competition was the focus of a Vertically Integrated Project (VIP) class. Through this class, undergraduate students can work as a team for several semesters on a project involving graduate students and faculty members. As the class finished in May and most students went away on internships, new students joined the team for the summer. The competition is a great way to get students to learn about robotics and apply what they learn in the classroom to a concrete project. For senior or graduate students, it is also a great experience on teaching and transmitting knowledge to junior students.

The new vehicle, named *Plongeur* after the French submarine that inspired Jules Verne when he wrote ’20 thousand leagues under the sea’, is the result of this team effort to build on the lessons learned at the 19th RoboSub competition and to design a more reliable, easy to maintain vehicle.

II. DESIGN STRATEGY

The team was divided into three groups of 3 to 4 students: Mechanical, Control/Navigation, and Sensing. The whole team met once a week to discuss progress and coordinate on decisions affecting several groups (for instance the placement of a camera). Each group met at least once more during the week. During the Fall semester, the team focused on adapting the submarine to interface with an autonomous WAM-V in order to compete in RobotX. Although the work was not finished in time, the knowledge gained by the whole team helped for the transition to RoboSub in the Spring semester.

This year the focus was put on documenting to ease the integration of new members, knowledge sharing, and on core tasks.

Indeed, one of the problems that became clear during the design process last year was the concentration of knowledge on too few people. This resulted on too much pressure being put on some members of the team, while others could not make progress because of a lack of available information on specific aspects of the system. To address this issue, tutorials and presentations were made during the year to document some of the hardware and software aspects. Moreover, during the pool tests, the person in charge of monitoring and controlling the vehicle through the base station computer was rotated so several members of the team had experience setting up and controlling the vehicle.

The second issue was that last year, the team spread too thin by trying to address every task. The strategy for this year has been to focus on the first three tasks and the pinger localization, and leave the tasks requiring actuation capabilities (Torpedoes, bins...) as future work. Next year the goal will be to integrate actuators to the vehicle to tackle the fourth and fifth task. Moreover, to additionally keep a sustainable workload, off-the-shelf or pre-existing solutions were to be used when possible.

The vehicle that had been designed for last year's competition was used as a baseline. Lessons learned at last year competition were the drivers for the redesign of the vehicle. The major design decision taken was to redesign the frame to have a more stable vehicle with only four degree of freedom (surge, sway, heave and yaw), while insuring positive stability for the two-remaining degrees of freedom (pitch and roll). Additional constraints were to design better attach points between the main hull and the frame while increasing the usable space on the frame for sensors and thrusters, and to add a separate external case for the batteries.

Table 1: Overview of Plongeur

Dimensions	16”x34”x14”
Weight	45lb
Propulsion	3 Blue Robotics T200
Cameras	2 Genius WideCam F100
IMU	Microstrain 3DM GX3-25
Pressure	MS5803-14BA
Computer	Intel NUC i5
IO	2 Arduino Mega
Software	ARCS

III. VEHICLE DESIGN

A. Mechanical

1) Main Hull

The main hull of last year AUV is reused. It consists of a foot-long transparent PVC tube of 8 inches in diameter. A transparent front plate is glued on one end of the tube, while on the other end a custom PVC flange with an O-ring groove is attached. The design of the O-ring system was done following the guidelines of the Parker O-ring handbook [3]. A back plate that let connectors through can be mounted onto the flange. It performed well last year, as not a single leak occurred. It is convenient to work on the electronics inside thanks to a drawer system that allows easy access to all the electronics. Opening and closing the hull takes a significant amount of time as all the connectors must be unplugged first, and caution must be applied when tightening and untightening the front plate. Last year the hull had to be opened after each run to replace and recharge batteries, which took twenty to thirty minutes and caused risk for the waterproofness of the main hull. Hence, this year it was decided to reduce the need to open the main enclosure by using an external battery case to store the computer and thruster batteries. The team used parts of the 4” watertight enclosure system by Blue Robotics to design the case. The Blue Robotics flange is used with a customized laser cut end cap compatible with the team’s waterproof connectors.

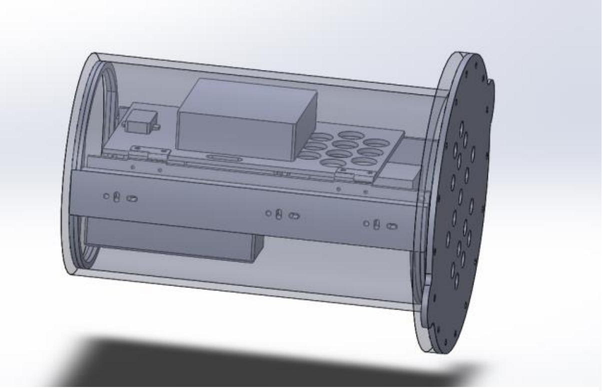
Figure 1: CAD rendering of the main hull

2) Frame

PVC collars were designed to hold the main hull and provide attach points for the frame and external components. The first iteration of the collar design was a full circular collar with a single clamping bolt. The collar is cut out of a thick PVC sheet using a waterjet, and with this form factor a lot of material is lost during the manufacturing. For the second iteration, a half circle shape with two clamping bolts was selected instead, allowing for less waste of the expensive raw material.

Last year’s frame was made of extruded aluminum, making it easy to manufacture, modify and to attach external components to it. The same material was used this year. The requirements for the frame design were that the vehicle must be able to sit flat to allow easy handling, the frame had to allow for adjustable thrusters and weight placement as the final design was not fixed when the design of the frame started, and allow enough room for future addition such as a pneumatic system for actuators.

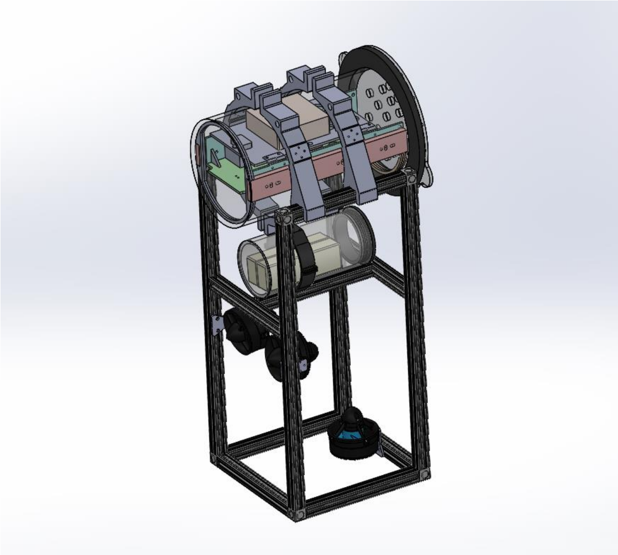
Figure 2: CAD rendering of Plongeur

Although unusual, a tall frame allows for an easy placement of components with very few interactions between them and allows for a reduced number of thrusters. The vehicle is extremely stable around the neutral roll and pitch position. A single thruster can be used to control depth. Two remaining thrusters control the motion forward and the heading of the vehicle. Analysis of the rules showed that there is no significant advantage in having a more hydrodynamic shape in the competition. A fourth thruster might be added to control sway before the competition starts, if time allows it.

3) Propulsion system

Last year the team built custom thrusters. Although they performed well for the length of the competition, some of them corroded. The team decided to buy off-the-shelf thrusters. Blue Robotics T200 thrusters are controlled in the same manner as our previous thrusters, and offer a large amount of power at a relatively low cost. Indeed, designing custom thrusters would only have yield uncertain performance for a marginal cost reduction and many additional hours of work. The process of deciding whether to manufacture the thrusters in the lab or purchase them from an external source was a good opportunity for the team to experience the "make or buy" decision that is prevalent in vehicle development. Brushless motors, such as the one found in the T200 thruster, are controlled by Electronic Speed Controllers (ESC). The vehicle is equipped with 30A AfroESC reprogrammed to allow rotation in both directions.

B. Electronics

1) Pressure sensor and IMU

The team uses a Sparkfun Pressure sensor MS5803-14BA. Last year the pressure sensor was the source of several issues due to the corrosion of the wires at the connection between the sensor wire and the cable connected to the hull. This design flaw required significant effort to manage throughout the competition. The sensor itself performed flawlessly, giving relatively accurate and precise measurement underwater. For this reason, the team decided to continue using the same sensor and include it directly onto the back plate, to ensure the wires are never in contact with the water. The sensor board is covered in Epoxy ensuring waterproofness and adhesion to the plate.

The team uses a Microstrain Attitude Heading Reference System across all its vehicles. It is the most expensive element of the vehicle, and is critical in the control of the vehicle. The IMU gives accurate estimation of the vehicle attitude represented by a quaternion. The use of quaternion rather than Euler angles avoids the issue of gimbal lock, which although almost impossible given the stability of this vehicle, sometimes occurred in the previous configuration in the simulation.

2) IO Boards

Arduino boards are used as the interface between the main computer and low level sensors and the Electronic Speed Controllers (ESC). The Arduinos communicate with the main computer through a custom serial protocol.

Table 2: Communication protocol

			Message				
Start_byte	Device_ID	Message_ID	Data	…	Data	CRC	End_byte

The device ID uniquely identifies the board, allowing the computer to recognize whether it is a sensor or motor board that is being plugged in. A cyclic redundancy check (CRC) is added to the message to ensure no error has occurred. If the start or end byte appear in the message, an escape character is added before the byte.

3) Hydrophone System

The role of the hydrophone system is to localize an ultrasonic pinger in the pool based on the time difference of arrival (TDOA). Indeed, the relationship between the time delay δt, the velocity of sound in water c, the spacing between hydrophones x and the angle formed by the pinger, the center point between hydrophone and the normal to the hydrophone θ is given by the following formula:

$$sin\theta = \frac{\delta t. c}{x} \quad (1)$$

Meaning that the direction of the pinger relative to the submarine can be found by estimating the time difference at which the 'ping' reaches each microphone.

The first step in performing the time delay estimation is to convert the acoustic signal to an analog signal. This is done by two Teledyne hydrophones mounted as far as possible on the structure, to maximize x and increase the system resolution.

Then, this analog signal is filtered and amplified to guarantee that the analog signal can be processed in the next step by the Analog to Digital Converter (ADC). The team designed a single supply band-pass filter to filter signals outside of the range of interest (25-40kHz) [1]. A PCB was designed using Eagle and manufactured using an Othermill Pro (Figure 2). As can be seen in **Error! Reference source not found.**3, the filter response is relatively flat in the range of interest and successfully attenuate high and low frequencies. Removing higher frequencies is especially important for digitizing as the digitizing frequency must be at least twice the highest frequency present in the signal (Shannon Theorem). A programmable amplifier is then used to amplify the resulting signal. The signal must be loud enough to be over its minimum threshold, but not so much as to saturate it.

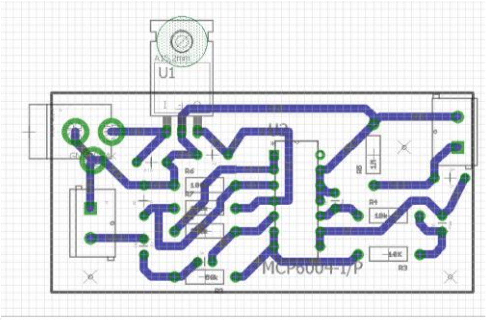

Figure 2: Filter board layout generated with Eagle

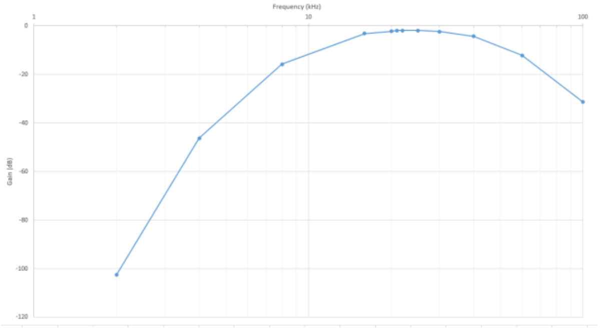

Figure 3: Filter Bode diagram

The signal acquisition is done by a StarTech external sound card. The StarTech is a low cost, small, external sound card that can be plugged in the main computer by USB. It can sample up to 96kHz, which is above the Shannon limit for the pingers (25-40kHz). By performing a cross-correlation between the two signals or between each signal and an idealized pinger signal, the time difference between each ping can be identified, which gives the direction of the pinger relative to the submarine.

4) *Camera*

The vehicle is equipped with two webcams, one pointing forward, the other pointing down. Last year, the team encountered many difficulties in waterproofing the rectangular parallelepiped that enclosed the bottom facing camera. To reduce the number of edges, that are as many possible points of failure, a cylindrical case was designed this time. The webcams have a wide field of view of 120 degrees. This is important because due to the water refraction indices being higher in water than air, the field of view is actually reduced to only 80 degrees.

5) *Power*

The computer and propulsion systems are each on their own battery to avoid voltage fluctuation at the computer. The batteries are 4 cells LiPo and respectively have a 6,000 and 10,000mAh capacity, which allows the team to not have to change the batteries while testing. Both batteries are stored in an external case making it easy to swap.

6) *Status*

An issue that was noted last year was that once the submarine was closed, it was hard to quickly be able to tell if everything was working as expected. During the limited slot of time allowed to test, if the vehicle was not behaving as expected, having to connect a computer and remote in the vehicle was taking a significant amount of time, when most of the time the problem was trivial (such as kill switch not on, or a disconnected board). To allow for an easy diagnostic, LEDs and a 4 lines LCD display visible through the translucent hull are used in *Plongeur* to display the state of the battery, sensors and kill switch. A similar system was used at RoboBoat 2017 and RobotX 2016 on the boats and was unanimously appreciated by the team.

C. *Simulation and control*

1) *Software*

The same software is used across all the vehicles of the Marine Robotics Group. The ARCS Software (Autonomous Robot Control and Simulation Software) allows to prototype and test algorithm in a simulation environment, provides playback capabilities, and a user interface to set up the missions. The software is written in C# and runs on Windows OS. The main advantage of this software is that the code used in the simulation is the same code that is run on the vehicle in real conditions.

The ARCS software was used at last year's competition, but significant improvements have been made since. The software allows to easily set up a course and a mission planner through a user interface. It has improved recording and playback capabilities, to allow the team to better track errors.

In Figure 4, the main window displays the simulation environment. The elements of the competition can be placed in the simulated Transdec using point-and-click on the map. The small window on the bottom right displays the simulated images from the point of view of the vehicle's camera, and can be rendered in the main window. On the bottom a console allows for warnings and status to be displayed to the operator. The right pane lets the user navigates between different user interfaces such as hardware, environment or planner, and save its settings.

Figure 4: Screenshot of ARCS

2) *Control*

One of the pieces of the ARCS software is the control class. The role of the control class is to map a motion or attitude required by a mission to actual motor commands. Closed-loop control of the vehicle is done through PID controllers. A user interface allows the gains to be easily tuned. Since the vehicle cannot accurately estimate its position or velocity, control of these states is done in open-loop. Closed-loop control is achieved for heading and depth. It should be noted that due to the highly-damped environment, proportional control alone is enough to obtain satisfying control. The controllers also allow to control heading and depth using feedback from the camera rather than the IMU when implementing a mission, allowing the vehicle to perform image based visual servoing (IBVS).

A dynamics model is implemented to represent the vehicle in the simulation. Constants are derived from the CAD, and tuned to reflect observations in the pool. The forces and moments acting on the vehicle are its weight, drag, buoyancy and thrusts. Drag is modeled up to the second degree and is considered to be applied at the center of gravity. Buoyancy is considered to be applied at the center of the main hull as it represents most of the volume of the vehicle. The point of application of each force is constant and the sums of moments and forces are used to compute the resulting acceleration of the vehicle.

3) *Vision*

To complete the various tasks based on visual cues, accurate processing and navigation using footage taken from the sub's onboard camera is necessary.

Last year, the team had attempted to test its image processing algorithm on computer simulated frames. However, the algorithm was a far cry away from being ready to apply to real footage. Some of the challenges associated with image processing in a realistic maritime environment had not been well modelled in the simulated frames. While this resulted in a disappointing performance last year, it provided an opportunity: namely to collect visual data on the starting gate, buoys and channel task, and used them to validate the new vision algorithms. Instead of relying simply on modelled images, the simulated images are tuned to ensure that they work with the real-world validated algorithms, which allow to test the interaction of the vision with the navigation in the simulation.

The algorithms combine shape and color recognition in different ways. Specifically, each task requires the integration of OpenCV functions into a more complex algorithm, although many of the steps remains common amongst the different tasks. To begin, edges are extracted from images using a Canny edge detector. Then, shapes can be identified from the edges using a combination of a Hough transform and various other shape detection functions built into OpenCV. From there, the geometries of objects related to the task at hand can be identified with the help of color recognition if necessary.

Analysis of the footage gathered at last year's competition as well as additional test footage filmed in the Georgia Tech diving well revealed a few factors that decrease the accuracy of the image processing algorithms. First, underwater conditions not only made the edges of objects less defined but also changed the way colors appeared. Second, other objects such as rocks in the Transdec pool as well as reflections from the sun, added noise to the image and additional edges to the subsequent output of the Canny edge detector. To combat these issues, the algorithms use a scoring system as well as a comparison with the output from previous frames so that only the most likely object can be identified, even if that object's shape and color are not clearly defined. However, the difficulties of underwater image processing are still apparent. Objects that are far away are nearly impossible to make out, and colors such as green are far more difficult to distinguish from the color of the water itself.

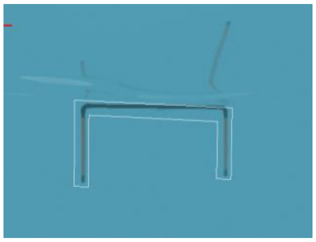

Figure 5: Gate identification in simulation

Figure 6: Gate identification with real footage

To further improve the accuracy of the algorithms used, additional fine tuning will be needed to adjust various threshold values and scoring mechanisms based on the underwater conditions at the competition. Although the physical requirements for the sub only consist of a functioning camera, other attachments are going to be investigated before the competition. A strong flashlight will be attached, in hope to improve visibility of both shapes and colors. Additionally, the team might consider to attach a color palette of known colors to the sub in view of the camera to aid in color recognition.

4) *Navigation*

The mission class combines the result of vision algorithms, with behaviors to perform tasks. Behaviors use the information from sensors such as the cameras or the hydrophones to decide where to navigate. If no information is available, the behavior uses dead-reckoning until sensory information is available or the mission finishes. This occurs for instance in the starting gate mission: as the vehicle gets closer to the gate, the gate is no longer in the camera's field of view and the vehicle will keep its heading and speed until it sees the orange marker on the bottom of the pool or until ten seconds have passed.

The linking of missions is handled by the Planner. When a vehicle is near the end of a mission, the next mission is pre-started, which means the vision algorithm starts looking for the next target while the vehicle finishes the current mission. This allows to implement generic search behaviors that do not depend on what is being searched.

The logic behind the Mission class is shown in Figure 7 through a sequence diagram.

The sequence of tasks can be modified through a user interface that lets the operator tune the mission order and mission parameters without restarting the software, allowing for fast on-the-fly modifications.

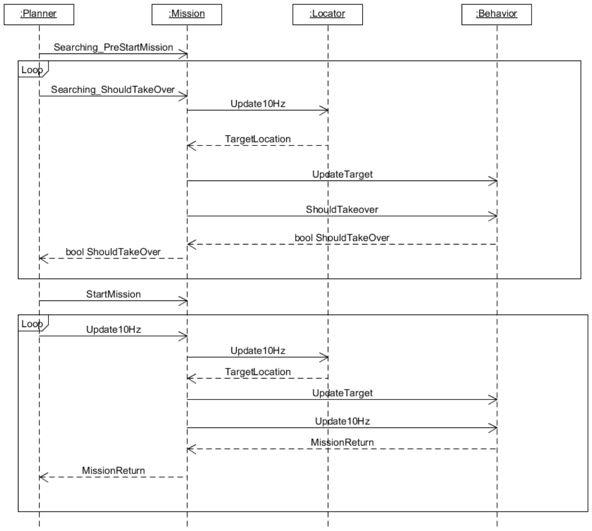

Figure 7: Sequence diagram of a mission

IV. PRELIMINARY RESULTS

Before submitting this paper, the team performed a total of five pool tests of two hours each in the Georgia Tech diving well. The tests were useful to debug issues with the state estimation that could not be identified in the lab. They were also used to calibrate the thrusters. Indeed, the T200/ ESC combination not only has a dead band around the neutral command, but also shutoff values when commanding maximum or minimum speed to the ESC. Once the thruster has reached that shutoff value forward or backward the ESC must go back to neutral for the thruster to start again. To avoid this situation the command to the ESC is clamped between the allowable values. Those values were identified at the pool to avoid running the motors outside the water. Significant redesign of the frame occurred in the past month, and only one test was performed with the new configuration. During that test the control gains were tuned and the vehicle demonstrated very good stability and controllability.

Parts of the hydrophone system was tested in the pool using a Teledyne Pinger similar to the one used at the competition. Analysis of the recordings taken at the pool shows that the algorithm can discriminate the position of the pinger between left and right, the accuracy will be investigated in more details once the system is mounted on the vehicle.

Currently the cross-correlation is done between the signals received at each hydrophone, and the time delay is identified by finding the delay at which the cross-correlation is maximum. Additional analysis in Matlab showed that cross-correlating each signal with an idealized 'ping' and comparing the results, might give more robust results, especially in a noisier environment.

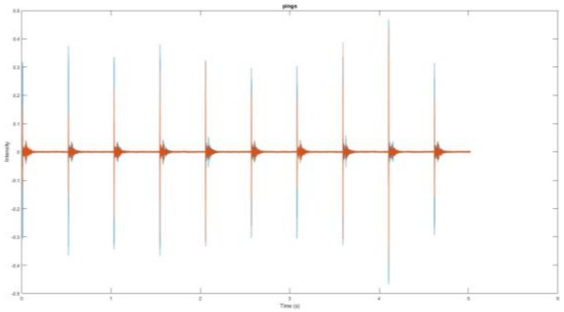

Figure 8: Audio recordings of an ultrasonic pinger at 33kHz at a 2Hz rate in the Georgia Tech diving well

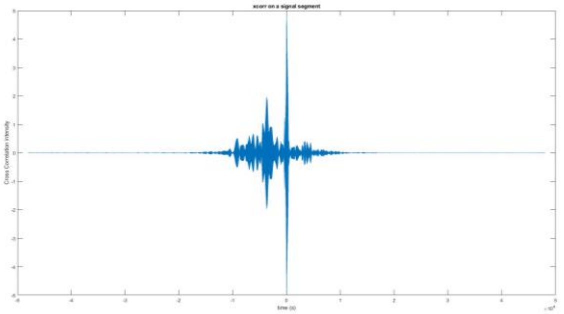

Figure 9: Cross correlation of signals received at each hydrophone, corresponding to an angle of 50 degrees to the left

V. CONCLUSION

The team plans to continue and intensify testing in July. The next tests will be focused on adjusting the buoyancy of the vehicle by adding weights to reduce the load on the depth control, stress testing the controller to make sure the vehicle recovers the right attitude even if it were to hit an obstacle, and finally start testing the behaviors for the buoy task in the pool. The goal is to arrive at the competition with a fully controllable vehicle and not have to make hardware or electronic changes on site with the hope of focusing exclusively on software.

VI. ACKNOWLEDGMENTS

The team would like to thank Georgia Tech Aquatics Facilities for letting them test in the pool.

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