Design Rationale for *Leviathan* Autonomous Underwater Vehicle

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I.

***Abstract*—The Kennesaw State University Autonomous Underwater Vehicle (AUV) Team designed and built the Leviathan AUV over the course of one year. Designing from the ground up, the team's ambition to complete as many of the 2017 RoboSub competition's tasks as possible manifests itself in mechanical claw and dropper attachments, a self-propelled torpedo system, and machine learning based object recognition. This machine's design and manufacture require communication between students of varying disciplines and self directed learning of advanced concepts.**

I. Design Strategy

During this team's prior appearance at the 2016 RoboSub competition, the former AUV model, *Cthulhu*, qualified for semifinals by passing through the start gate. From this starting point, the aspirations for the next iteration have only increased. The design goals for *Leviathan* were to complete each vision task, cultivate pearls, battle a squid, and collect and classify samples.

Achieving these ambitious goals requires the team to make vast improvements and additions over a short time frame. Mechanically, *Leviathan* requires a mechanical claw, a system to drop markers, and a torpedo launch mechanism. From a software standpoint, the AUV needed the necessary vision and motor control requirements to implement these mechanical systems, as well as a functioning hydrophone system to detect the pingers' frequencies and navigate the competition properly. These changes enable *Leviathan* to attempt nearly every challenge presented in the 2017 RoboSub competition.

II. Vehicle Design: Mechanical

A. Outer Structure

In order to progress in the current and future competitions, the outer structure's redesign must account for the following: modularity, durability, and reliable waterproofing. The eventual design, shown in *Fig. 1*, features four 1 inch Delrin plastic side plates waterjet to reduce weight, and two 8020 aluminum posts. This structure supports eight BlueRobotics T200 thrusters, each producing 20 lbs. of thrust, and a waterproofed acrylic housing. The realization that the sub lacked a necessary degree of freedom, pitch, prompted the accommodation of two more thrusters in this iteration. This realization and modification proved to be one of the greater challenges with its design. The other difficulty in its design was its weight; the materials chosen, while durable, tend to be quite heavy, so its weight must decrease both to be within the acceptable weight range and remain positively buoyant. Therefore, weight reduction presents itself as an essential future goal.

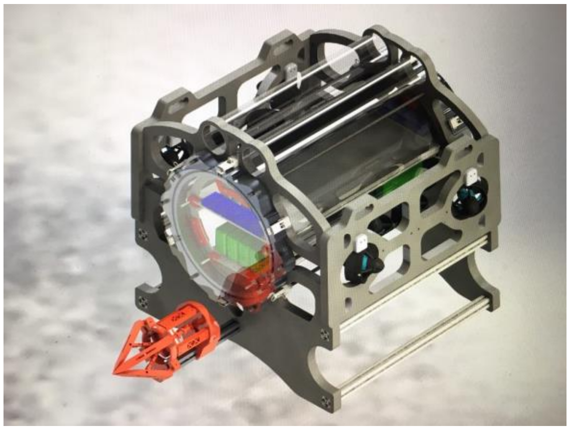

Fig.1: *Leviathan Initial Design Render*.

B. Housing

The aforementioned acrylic housing, arguably the most crucial piece of structure on the sub, houses the onboard electronics and protects them from the sub's aquatic surroundings. This piece is also a new addition; the fact that the prior waterproof housing was rated waterproof only up to three feet in depth prompted this change. The clear acrylic cylinder measures twelve inches in diameter and twenty four inches in length. Acrylic proves itself to be an ideal material for this purpose because it is lightweight enough to minimally counteract its buoyancy, and transparent enough to contain cameras.

In order to sufficiently waterproof the inside, for merely one drop of water proves disastrous, the team designed two aluminum flanges each containing two rubber O-rings. The unremovable back end flange contains fourteen holes cut via waterjet. These holes will contain waterproof connectors, as detailed under "External Electronics". The front flange, conversely, can be removed to access, modify, or remove the inner electronics. The fact that it also contains an acrylic component permits a front facing camera to view the competition field. The manufacturing for such important, detailed pieces proves difficult for our regular resources. However, the Temel Gaskets company accepted technical drawings of our design in order to manufacture them.

C. Inner Structure

Within the acrylic housing lies the inner structure. Its design must accommodate all of the sub's electronic components, allow for ease of access to the electronics and the onboard computer, act as a sufficient heat sink, keep components from shifting with movement, and modular enough to change with any future upgrades. Partially manufactured from ABS 3D printed plastic and water-jet 6062-T6 aluminum sheet, it balances heat sink capability and durability with a slightly decreased weight. The biggest challenge presented itself as the cylindrical shape, as seen in *Fig. 2*, of the sub, which is notably more difficult to design for than our prior rectangular housing.

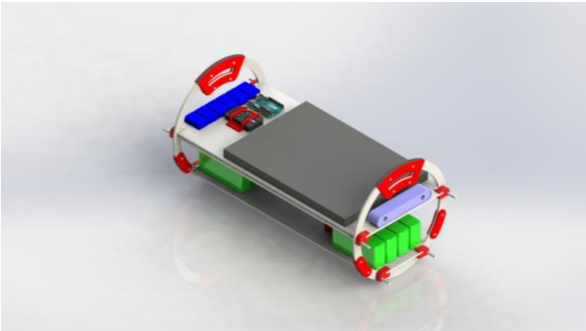

Fig. 2: *Leviathan's inner structure with its electronics*

D. Mechanical Claw

The mechanical claw, displayed in *Fig. 3*, will be mounted with the fingers parallel to the forward direction of the craft, just within the vision of the ZED. Mechanically, it uses one Savox servo to open and close its fingers around object, ensnaring them in such a way that precision is not required. The servo, generating 22 Kg*cm of torque, should be able to exert enough force for the grip strength of the fingers to not fail when picking up larger objects. The vast majority of the grabber will be 3D printed of ABS plastic, with crucial parts (geometry willing), being milled out of high strength acrylic via a computer numerically controlled (CNC) mill. The parts to be manufactured via CNC consist of the both gears in the image, and the fingers themselves.

When creating this subsystem, the team sought to overcome several challenges. The claw was to operate on one servo with a limited rotation range, but to maximize the movement range of the fingers in conjunction with said servo is essential to its task. To combat this, the gear system was designed base on $S=r\Theta$, so that the 130 degree rotation of the servo would translate to at least two full rotations of the central gear. Using one servo had both advantages and disadvantages, however it allows a decrease of the weight of the claw, which led to a final weight of just under 2 pounds. In the future, there are several obvious improvements that will be made, from the movement of the grabber relative to the sub, to the precision of the grabbers grip range. To allow for expanded axes of mobility, creating an "arm" that can move in at least relative axes will prove itself necessary. To make the gripper more precise, other design options will need to be explored, to include modifying or creating a servo that does not have a limited rotation rate, or using more than one servo.

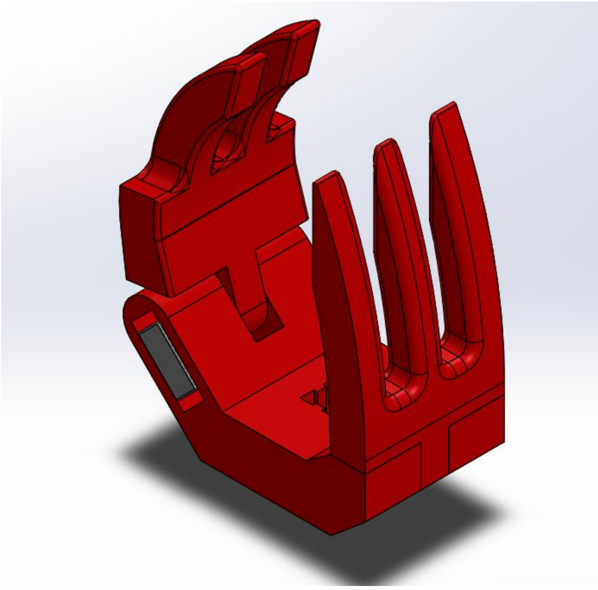

Fig. 3: *Leviathan's mechanical claw attachment.*

E. Dropper

In order to complete the "cultivate pearls" task, the team designed a dropper to deliver the markers, a payload of four 1 inch diameter ball bearings. The bulk of the structure consists of a large cylinder containing eight smaller cylinders, much like a revolving door, as shown in *Fig. 4*. Each chamber can carry up to one marker. Driven by a Hitec HS-5646WP servo capable of turning 180 degrees, the 8 mm aluminum rod attaches to a circular plate with 45 degrees cut out. As the servo rotates the plate, the markers fall from the housing. The team manufactured the housing, plate, and all connecting pieces with ABS plastic via 3D printing. This system may improve in the future by a change in the gearing to accommodate a full 360 degree range of motion, or a modification of the housing to not have unusable chambers.

Fig. 4: *Leviathan's Dropper*.

F. Torpedo Structure

In order to implement the torpedoes, the AUV requires a containment structure for the missile components. This structure consists of two 3-inch inner diameter acrylic pipes 24 inches in length. Because the propelling system of the torpedoes has more of a basis in electronics more than mechanics, we filed the details for their construction under "Vehicle Design: Electrical".

III. Vehicle Design: Electrical

A. External Electronics

The sub makes use of BlueRobotics cable penetrator connectors and one MacArtney Subconn Ethernet connector to facilitate waterproofed connections from the external electronics to the non-waterproof inner electronics, the communication between which appears in *Fig. 5*. Rated at 300 V from 5 to 10 amps with a pressure rating of 700 bar, the MacArtney Subconn Ethernet connector is used for communication to and from the sub. The wet mateable connector saves time when uploading new code. Leviathan utilizes eight BlueRobotics thrusters, brushless DC motors encased in ABS plastic housings, for maneuverability. These thrusters produce a peak forward thrust of 5.1 Kg*f at 16 V and a peak reverse thrust of 4.1 Kg*f at 16 V. Eight electronic speed controllers (ESC) control and regulate the speed of the thrusters. The ESCs receive instructions by pulse width modulation from the PixHawk and give users the ability to control the rotational speed and direction of the thrust.

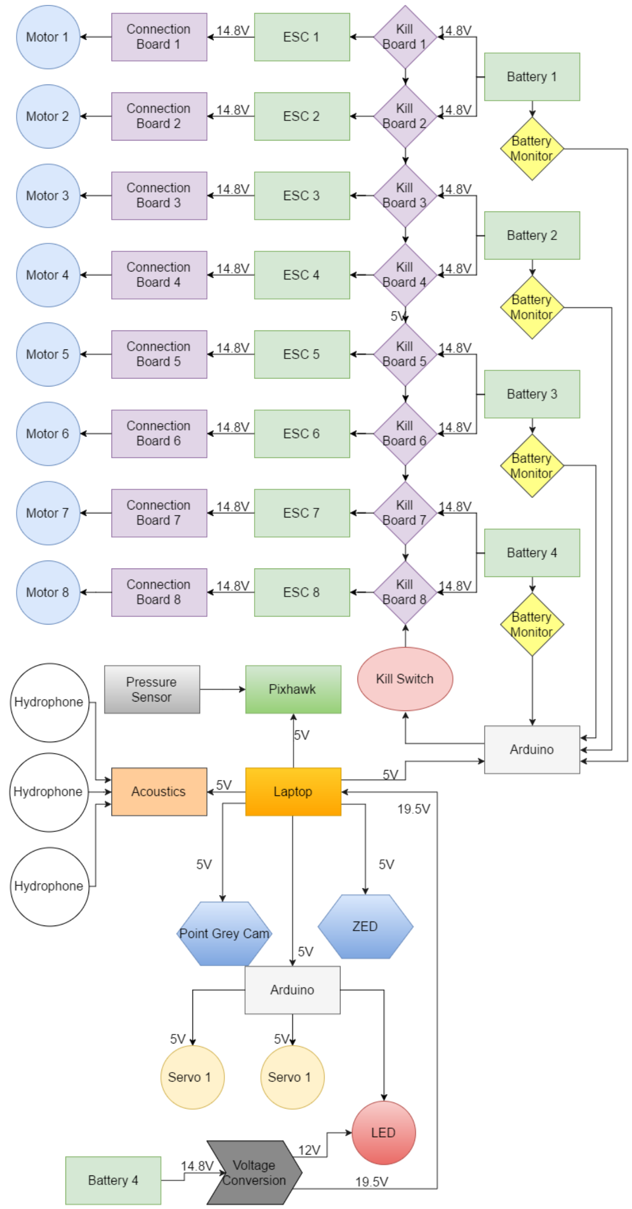

Fig. 5: *Electrical Wiring Diagram*

B. Torpedo System

The goal of the torpedo system is to have a completely isolated system by which we could fire the torpedoes. Separating the torpedoes from the sub by way of light signals achieves this goal. The torpedo system consists of four hollow 3D printed semi-modular torpedoes mounted with an external photoresistor and an Arduino microcontroller inside. A brushless motor attached to a propeller on the back of each torpedo launches the torpedo. To combat wild rotation from one spinning propeller, the torpedoes have been printed with twisted fins to provide a counter rotation as the torpedo moves through the water. Details about the torpedoes' design can be found in *Fig. 6.*

When *Leviathan* receives a signal to fire a torpedo, it flashes high power LEDs at a specific interval from inside the main sub housing. The photo resistors in the torpedo read that pattern into the Arduino and fire accordingly. One challenge in detecting the correct pattern of light was the constant changing of ambient light from sun hitting the water. Constantly adjusting the photoresistors' received baseline voltage resolves this issue.

Fig. 6: *Leviathan's Torpedo Render*.

C. Acoustics

Leviathan has an array of three Aquarian Hydrophones to determine the bearing of the pingers. The hydrophones reside on the front and bottom of the sub. The hydrophones signals pass through a U-Phoria UMC404 four input USB audio interface where they can be digitized and time stamped.

D. Battery Monitor

A minimum of four MultiStar lithium polymer (LiPo) batteries at 10000mAh and 14.8V can power the sub, which allows the sub to operate for many continuous hours of testing. HobbyKing LiPo voltage checkers monitor the batteries. They provide a digital voltage indicator and an alarm. The monitors connect to an Arduino. If the alarm on the monitors are triggered, the Arduino deactivates the motor and the AUV will rise to the surface.

E. Printed Circuit Boards

For the 2017 sub, the electrical division decided to design custom printed circuit boards (PCBs) in order to improve and simplify the circuitry. The plan to use EagleCad to produce our PCBs gave way to a decision to use Circuit Maker due to a superior parts library. The first challenge to overcome was the team's lack of prior Circuit Maker experience; the team had to start from scratch on learning how to design and export the files needed to build the PCBs. The PCB design proved to take the longest due to unfamiliarity with the software. Once each PCB was designed, the necessary files were submitted for a company produce the boards.

The team designed the main connector board as the hub for all the connections for each motor and servo. This design allows for ease of access to fix any technical issues. The main board contains three different types of connectors added onto it. The first and most complex type is the motor board. It uses two of the leads out of the three that each motor connects with. Its design provides that each connection is spaced out in a way to allow for heat dissipation. The second and third type of board correspond to servos necessary for the robotic arm, dropper, and camera. One version uses just eight connections as the minimum that the servo uses. The other version has four connections for servos that require more current. Each connection type has a different wiring to each pad for fourteen gauge servo wire, twelve gauge motor wire, and sixteen gauge wire for other connections.

F. Sensors

The sub has an full sensor suite, which corresponds to the events in whichthe team chose to compete. It has two cameras: one facing forward to locate and work through the challenges, and one facing the floor to handle line following for the movement to each successive challenge. One of the cameras is a Point Grey Chameleon CMLN-13S2C and the other is a ZED 2K Stereoscopic Camera. The pressure sensor that we chose was the Measurement Specialties MS5837-30BA, which can measure up to 30 bar with a depth resolution of 2mm. The pressure sensor keeps the sub within the proper range of the pool floor, ensuring the sub does not breach the surface unexpectedly. The Inertial Measuring Unit (IMU) detects changes in the vehicle's orientation in three major axes: pitch, roll, and yaw. Three Aquarian Audio hydrophone equip for the acoustic challenge.

G. Power Conversion and Distribution

Lithium polymer batteries power the sub. Each pack provides 14.8 Volts, 10000 mAh, a peak discharge rating of 20 c for 10 seconds, and a continuous discharge of 10 c. The sub power systems divide into two primary categories: computer and task, and propulsion. Separating these systems into two categories simplifies power distribution and reduces noise and crosstalk for electrical components. There are three primary voltage rails: the 12 V rail which powers the LED to instruct the torpedo to fire, the 19.5 V rail that will charge the laptop, and the 5 V rail which powers sensors and controllers.

Two buck converters, which step-down voltage while stepping up current from its input to the load, handle the 12

V and 5 V conversions. The buck converters were chosen because they are 80% to 90% efficient at stepping down voltage. The 19.5 V conversion is handled by a DCDC-USB-200 intelligent buck-boost DC-DC converter with USB interface. This converter allows us to monitor the LiPo pack voltage and vary the output voltage and current from are custom script that is program on the board.

IV. Vehicle Design: Software

A. Operating System

The software architecture of the sub, as explained in *Fig. 7,* is based on Robot Operating System (ROS) kinetic. It allows access to precompiled and developed packages as well as a foundation to provide feedback to the ROS community [1]. The software division has created separate packages which encompass several tasks. Some notable include: Sub_Ai_State_Manager, and YOLO_Objective_Executer, PI_Loop. Community source open sourced projects handle a number of major functions; they include but are not limited to: SMACH, MavROS, rosserial, zed_ros_wrapper.

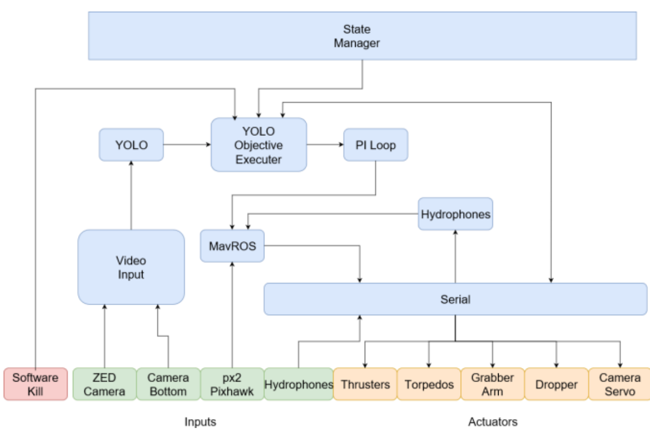

Fig. 7: *Leviathan's software architecture.*

B. Autonomy

Autonomy occurs through a high level decision tree to control the state of the machine and the functions it will execute. State Machine (SMACH) is a package in ROS that provides these functions. Each state can be user defined for greater control [2]. Each state triggers a series of functions which work together to complete the competition's tasks. SMACH contains a built in graphical interface to easily debug and view the current state the program is in.

C. Vision

Video input is handled by a new hardware that is being testing this year. The ZED Camera is a stereoscopic camera which can output independent left/right camera feeds, a depth map, and a point cloud map [3]. This year is the first in which the software team has access to point cloud data and can test the functionality of the camera for underwater use. Because underwater environments tend to be featureless, the hypothesis was that may be difficult to implement. The intention was to localize *Leviathan* to other objects that are in the pool. Currently, the camera will collect data to determine if localization with SLAM is achievable via zed_ros_wrapper, which collects all of the data outputted by the camera into a format that can be recorded [4].

D. Machine Learning

Much of the RoboSub 2017 competition relies on a reliable method to track various objects underwater. Due to the noise and variability of the environment, the light-scattering effects of water, the lack of information about how new objects will appear in this environment and time constraints, our software division deemed the use of machine-learning based object detection more economical than the creation of traditional hand-crafted detection algorithms. The recent success of YOLOv2, a Convolutional Neural Network designed for object detection and localization, at various datasets such as Microsoft COCO: Common Objects in Context and PASCAL Visual Object Classes persuaded the software division use a network with a similar architecture [5].

A dataset of the objects in the Robosub 2017 competition must be created in order to train YOLOv2 to recognize objects. The creation of such a dataset entails labeling the location of objects in images from competition runs. Because YOLO is a large network, it is very prone to overfitting if trained from random initialization on a limited amount of data. To reduce this risk and allow for learning from a smaller dataset, the method of fine-tuning a pre-trained model is employed. Tests using data collected by our team indicate YOLOv2 is sufficient to perform object detection for this competition, as demonstrated in *Fig. 8*.

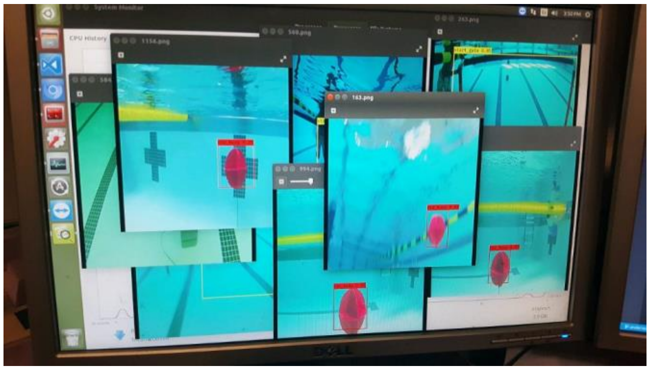

Fig. 8: *YOLOv2 Network in Action.*

E. MavROS

MavROS serves as an all-in-one package to control movement of the submarine [6]. Virtual RC values are published to the /rc/override channel as well as the Flight Mode for the IMU: a px2 Pixhawk. We used a flight controller for drones because there is an open source community for AUVs and remotely operated vehicles (ROVs) from BlueRobotics [7]. They created the Ardusub project fork from ArduPilot, and their firmware easily wraps into MavROS and MavLink [8].

F. Hydrophone Acoustics

A new addition to the sub is a hydrophone array. The input is recorded via a Behringer U-Phoria UMC404HD DAC on the host machine to 88.2kHz sound files. An analysis on the files finds the four loudest frequencies at any give time between (25 - 40) kHz with a Fast Fourier Transform (FFT) at each interval. It records the loudest frequency as the closest pinger and assigns a timestamp. The sub uses the timestamps in conjunction with an equilateral triangle array to determine a heading which is output into a vector. The vector is converted into /rc/override for the MavROS package [9].

G. Navigation and PI Control

The PI controller is a variation on the PID controller. By omitting the derivative, quick implementation of a movement package and reduction of the amount of tuning necessary for our controller become possible. It takes two points from the field of view: one provided by YOLO and one provided by the center of the camera. The program uses both the differences in the x and y directions to calculate the distance between the two points and obtain the error. It then processes the error through the control loop and outputs a data point that is converted into an RC value published to MavROS.

H. Arduino Auxiliary Control

The functions required for control of the dropper, mechanical claw, and torpedo mechanisms require an external interface. An Arduino easily connects via serial to these objects to communicate on a low level system; in these situations, to execute a higher level communication may be difficult. The Arduino has large support for integration into ROS, and can run independently from any of the higher level functions because it has its own microcontroller [10].

V. Experimental Results

The three occasions on which the Kennesaw State University Marietta campus pool was reserved to test and improve our systems provided the team with important data. Each instance was dedicated to gathering video footage of the start gate and the red and green buoys. Given that lighting at the competition will not be consistent, the lighting in which we tested was variable so that *Leviathan* might somewhat consistently recognize these obstacles. Labeling the data gained and training the recognition software accordingly affords a consistent computer vision solution.

VI. Acknowledgments

The team would like to thank Temel Gaskets for their crucial support in manufacturing our O-rings and end caps. The team would like to thank the KSU Alumni Association and the KSU Student Activities Board and Council, from whom this project derives the bulk of our budget. The team also would like to thank our faculty advisor Dr. Kevin McFall, as well as all of the Kennesaw State University professors who have taught the team’s members much about engineering and technology. Lastly, the team would like to thank SolidWorks for their support with our student licenses. Without each of these parties’ contributions, this project would not reach the point that it has.

II. VII. Appendix—Outreach Activities

In an effort to reach out to the metropolitan Atlanta community, this team appeared at Maker Faire Atlanta in October of 2016. The team brought the prior model, Cthulhu, a remotely operated mini-sub in a water-filled tank, and prototypes of some of the mechanical sub-systems for Leviathan. This event provided the opportunity to teach attendees, a large number of whom are young children, about robotics, mechanical design, and the engineering process. The team hopes to have inspired visitors to learn more about technology-related fields and robotics.

III. VIII. APPENDIX--REFERENCES

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