Technical Design Report for Via Maris

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***Abstract*— The Kennesaw State University Autonomous Underwater Vehicle (AUV) Team built and designed Via Maris with the intent to modify and enhance it over seasons to come. Initially developed over the course of one year, the AUV's motor setup and control systems run in parallel with common technology being used in aerial drones. This vehicle utilizes a PixHawk flight controller, functioning as both a motor controller and gyroscopic sensor. The communications between both a dual camera system and aforementioned flight controller govern the movement of the AUV. Successfully creating an autonomous underwater vehicle entails communication and cooperation between team members in a multitude of different disciplines, including, but not limited to software and mechanical engineering.**

Keywords—autonomy, underwater, vision, design, navigation

I. Competition Strategy

At the team's prior appearance at the 2017 RoboSub competition, the former AUV model, Leviathan, failed to qualify for semifinals by passing through the start gate. Due to a series of failures in manufacturing, procurement, and design oversight, the sub was unable to perform at the level required for the completion of tasks. With this experience in mind, the mechanical team has set out to create a sub that will be equipped to accomplish the tasks as set by the competition. Thus, this year`s vehicle features components used in Leviathan, as well as new additions [1].

Achieving these ambitious goals requires the team to make vast improvements and additions over a short time frame. Mechanically, Via Maris requires a mechanical claw, a system to dispense markers, and a torpedo launch mechanism [1]. 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 Via Maris to attempt nearly every challenge presented in the 2018 RoboSub competition.

II. Design Creativity

A. Mechanical Design

1) Outer Structure: In order to progress in the current and future competitions, the outer structure redesign must be modular and durable and provide a rigid pressure vessel.The eventual design, shown in Fig. 1, features a frame constructed using 80/20 aluminum extrusions and precision-milled aluminum fixture points. This design supports eight BlueRobotics T200 thrusters 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 modification proved to be one of the greater challenges with its design. Another consideration was weight. The materials chosen, while durable, tend to be quite heavy, so we had to decrease the design's weight to be within the acceptable weight range and remain positively buoyant.

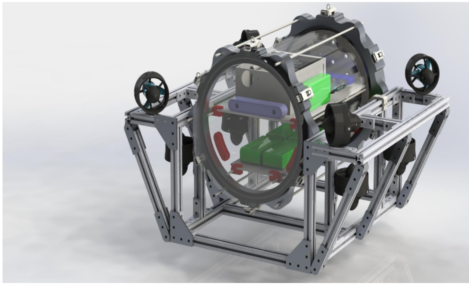

Figure 1: Via Maris Design Render

2) Housing: The acrylic housing, the most crucial piece of structure on the sub, protects the sub's onboard electronics from the sub's aquatic surroundings. This piece is also a new addition, which was changed because the prior waterproof housing was rated waterproof only up to 3 ft. in depth. The clear acrylic cylinder measures 12 in. in diameter and 24 in. in length. Acrylic is 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, the team designed two aluminum flanges, each containing two rubber O-rings. The irremovable back end flange contains fourteen holes cut with a 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. Its acrylic component permits a front-facing camera to view the competition field. The manufacturing for such important, detailed pieces proved difficult for our regular resources.

3) 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 be 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 that presented itself was the cylindrical shape of the submarine, as seen in Fig. 2, which is notably more difficult to design than our prior rectangular housing.

4) Robotic Arm and Deployment Mechanism: This year's competition makes use of manipulatable tokens in the form of golf balls, so our manipulator must be designed to retrieve, store, and deposit these objects. Several factors were selected to determine an effective claw and containment unit. The largest design challenge was to have a manageable margin of error for ball retrieval to limit the required robot positioning accuracy. The claw must effectively store and retrieve the token from an onboard storage system. It must also deposit these tokens accurately in the various scoring areas.

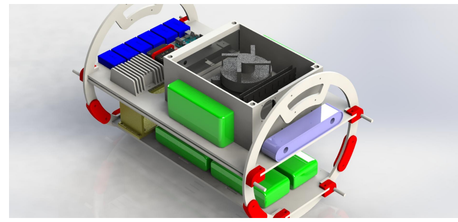

Figure 2: Via Maris Internal Design Render

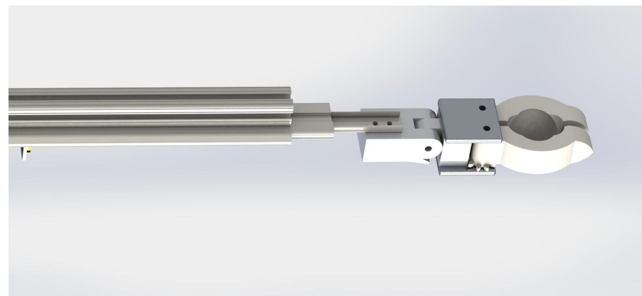

Figure 3: Robotic Arm Design

Several claw versions were considered with a funnel-like design similar to Fig. 3 for their margin of error in retrieving balls from the "Buy Gold Chip" objective. This design was originally planned with the requirement of catching the balls as they are released from the dispenser, with the attached tray now making this obsolete. This design is still effective at retrieving balls from the edges of this tray and needs no further modifications. The next requirement is that the arm assembly must have a storage system for the tokens, as preloaded tokens make this necessary. The most effective device is a 1.75 in. ID PVC pipe with a very weak spring, which is used to push the balls to the front of the tube. Attached just in front of this tube is a weak spring latch (Fig. 3) used for keeping the balls in the PVC tube but allowing their retrieval. Attached to the front edge of the claw is a pointed arch, which allows the claw to slide past the latch on the ball storage tube, both effectively storing and retrieving balls from it.

The arm itself makes use of a heavy duty drawer slide, a 300 mm lead screw, and a T-100 motor for rotation of this lead screw. The claw is attached to the end of the drawer slide and is pushed forward by the lead screw assembly as the T-100 motor turns. This gives the arm an effective travel of 254 mm or 10 in. in front of the submarine. This allows for camera visibility of the claw in operation, and for depositing the tokens into the surface for points. The claw has two servos attached; one for rotation of the wrist for ball storage, and one for opening and closing the claw itself. The 3D printed claw also has gears attached at its pivot points to allow symmetric movement of the claws and control with a single servo.

5) Torpedo System: For this year's competition, it was decided that torpedoes (Fig. 4) without onboard propulsion would be the most feasible. Unpowered torpedoes can be smaller, and we can fit more on to the submarine. In addition, we can store the compressed air tanks elsewhere on the submarine which allows for a more space-conscious layout. The primary manufacturing method used for the torpedoes was 3D printing. This has allowed us to design more intricate and aerodynamic systems, allowing for rapid manufacturing, redesigning, and testing, while staying within the allotted budget. The first design for propulsion

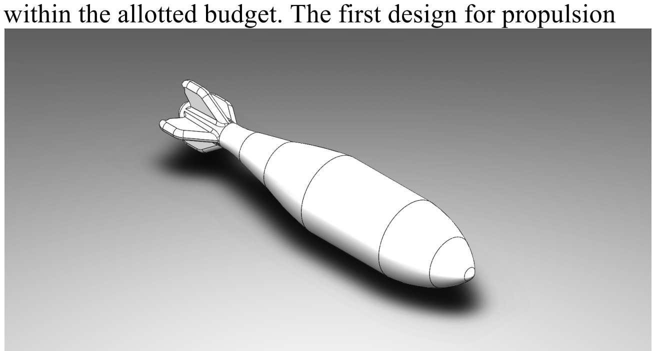

Figure 4: Current Torpedo Design

involved one 10 oz. paintball tank that would be pressurized to 300 psi, then four tubes move the air through flow restrictors which bring the pressure to 120 psi. Finally, electric solenoids join the flow restrictors to 2 in. PVC tubes with the torpedoes inside of them. The seal is created between the midsection of the torpedo and the inner wall of the tube. This means our fins cannot extend beyond this diameter, which reduces their effectiveness.

With the propulsion method designed, we moved onto the torpedoes. We based their design on torpedoes used by the military and designed the fins to maximize lift. Since we wanted the torpedo to be positively buoyant, we wanted the fins to slightly push the torpedo downward to keep the straightest line of travel between the tube and the target. We ran a few possible combinations of pressure, drag and lift coefficients, and distance to the target. Overall, we determined that since any rotation induced when the torpedo was launched could send it off course, shaping the fins to increase lift would likely do more harm than good. Going back to our original criteria for the torpedo, we thought about how finning would best increase stability and accuracy. The torpedo needs to consistently reach the intended target, and with experimentation, we arrived at the conclusion that the best way to increase accuracy was to induce a spin in the torpedo. Much like rifling in firearms, the spin keeps the torpedo from straying off course, and as it is traveling through a much more dense fluid than a bullet, the effect is magnified. With this in mind, the next step was performing a parametric "what-if" simulation in SolidWorks to find the dimensions that would give us the most torque and least drag. Using geometry from the initial design, the radii of the body, nose, and tail, as well as the angle of the fin and radius of the top and bottom of the fin, were adjusted and run iteratively through SolidWorks Flow Simulation Add-on with results shown in Fig. 5 and Fig. 6. This information was used to determine the most recent design.

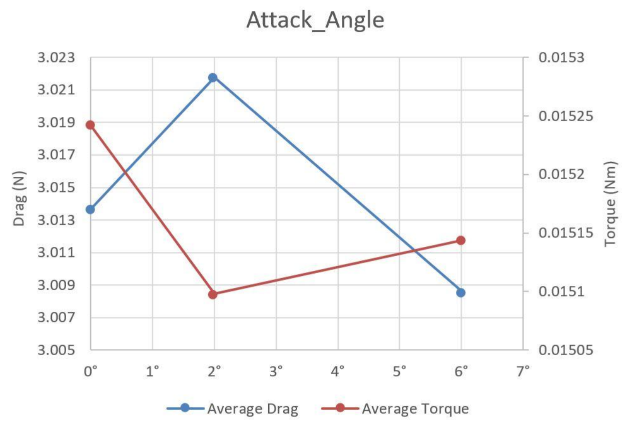

Figure 5: Flow Simulation Results for Attack Angle

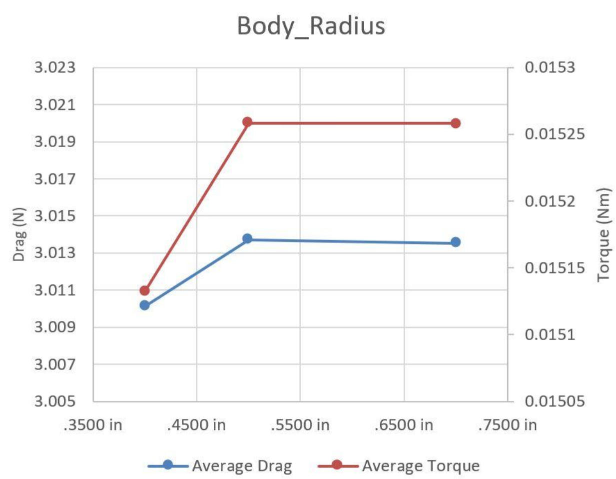

Figure 6: Flow Simulation Results for Body Radius

B. Electrical Design

1) 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, as shown in Fig. 7. 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. Via Maris 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 us the ability to control the rotational speed and direction of the thrust.

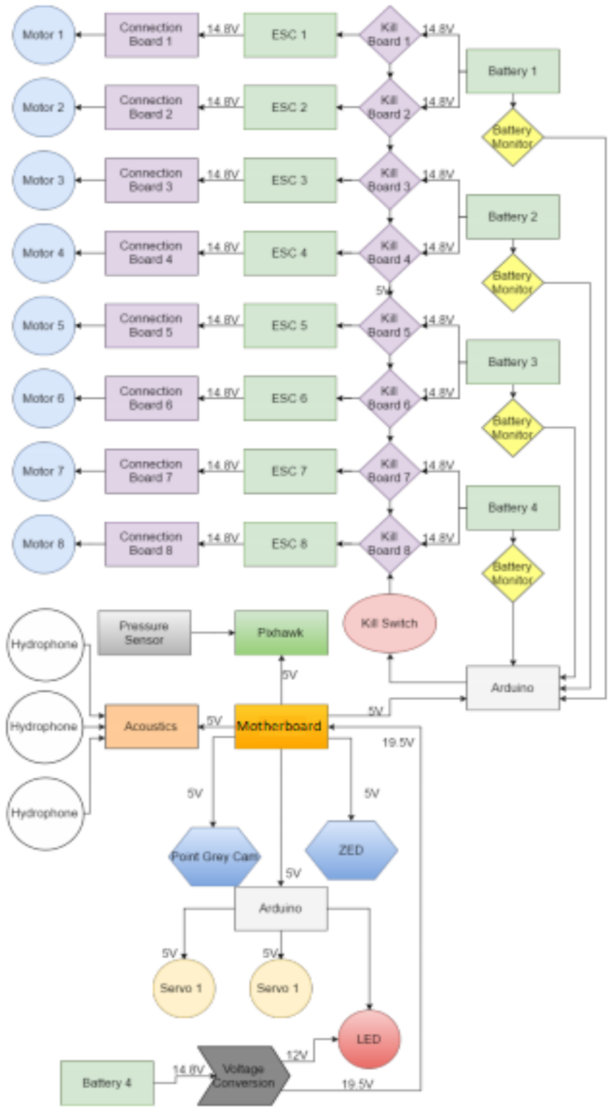

Figure 7

2) Printed Circuit Board: For Via Maris, the electrical division designed a new circuit board for our killswitch. The killswitch board uses MOSFETs where the gate is connected to an optocoupler which in turn is controlled by an Arduino-based potentiometer. The MOSFETs are set in parallel to minimize the heat output from each MOSFET and prevent burning them out.

3) Power Distribution: Lithium polymer batteries power the sub. Each pack provides 14.8 GV, 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 systems, and propulsion. Separating these systems into two categories simplifies power distribution and reduces noise and crosstalk for electrical components. There are two primary voltage rails: the 19.5 V rail that will power the motherboard and the 5 V rail which powers sensors and controllers.

4) Acoustics: Via Maris has an array of three Aquarian Hydrophones to determine the bearing of the pingers. The hydrophones are placed on the front and bottom of the sub. The hydrophone signals pass through a U-Phoria UMC404 four input USB audio interface where they can be digitized and time stamped.

5) Sensors: The sub has a full sensor suite, which corresponds to the events in which the team chose to compete. It has two cameras: one facing forward to locate and work through the challenges, and one facing the floor to track path markings for movement between challenges. 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 2 mm. 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 are used for the acoustic challenge.

C. Software Design

1) Operating System: The software architecture of the sub 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 [4]. The software division has created packages which connect to ROS to perform tasks needed to operate the AUV. Community open source projects handle a number of major functions; they include but are not limited to: SMACH, MavROS, rosserial, and zed_ros_wrapper.

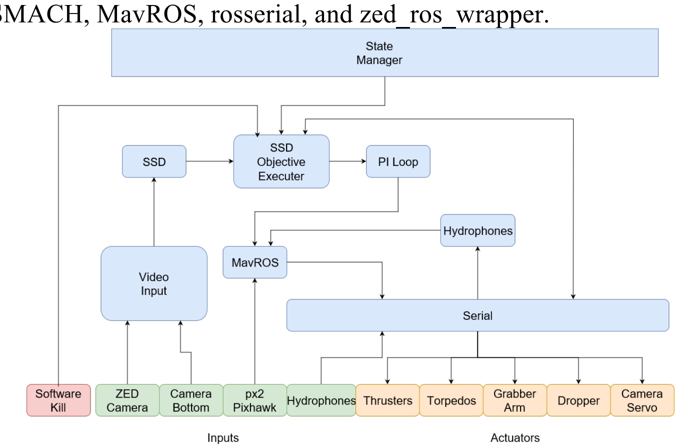

Figure 8: Software architecture

2) Autonomy: Autonomy occurs through a high level decision tree to control the state of the machine and the functions it will execute. SMACH is a state machine package in ROS that provides these functions. Each state can be user defined for greater control [5]. 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.

3) Vision: Video input is handled by a USB camera. Photos from the camera are sent to the neural network for processing through ROS.

4) Machine Learning: Much of the RoboSub 2018 competition requires 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 software division chose to use the SSD (Single Shot Detector) architecture with MobileNet because of its performance, wide support, and hardware compatibility. SSD MobileNet on Caffe was known to work with the Movidius Neural Compute Stick, a USB vision processing unit designed for neural network inference which we are using.

A dataset of the objects in the RoboSub 2018 competition must be created in order to train SSD to recognize objects. The creation of such a dataset entails labeling the location of objects in images from competition runs. Tests using data collected by our team indicate SSD is sufficient to perform object detection for this competition.

5) MavROS: MavROS serves as an all-in-one package to control movement of the submarine [6]. Virtual RC values are published to the Pixhawk flight controller. We used a flight controller for drones because there is an open source community which developed custom firmware which allows these flight controllers to control AUVs. They created the Ardusub project fork from ArduPilot, and their firmware easily wraps into MavROS and MavLink [7].

6) 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 between 25-40 kHz at any given time 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 [8].

7) 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 SSD 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.

8) 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 support for integration into ROS, and can run independently from any of the higher level functions because it has its own microcontroller [9].

III. Acknowledgments

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