Texas A&M Women in Engineering Design and Implementation of Autonomous Underwater Vehicle

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Abstract—Autonomous Underwater Vehicles (AUV) allow scientists to implement unmanned exploration of marine environments and collect highly detailed seafloor sonar and optical images. AUVs are commonly used in the fields of oil and gas, environmental monitoring, and search and recovery.

An Autonomous Underwater Vehicle was designed and developed by the Texas A&M University (TAMU) Women in Engineering (WE) AUV team to compete in the annual RoboSub Competition. The TAMU WE AUV team consists of over 20 active members from various engineering disciplines. The design and development of the AUV consisted of three subdivisions: Electrical, Mechanical, and Programming. The electrical subdivision entailed the power efficient design of the overall electrical system of the AUV and interfacing of the sensors, programming subdivision developed algorithms for image processing and data analysis to control the AUV's movement, and mechanical subdivision focused on the small form factor design of the frame and hull, smart waterproofing of various sensors and cables, and ensuring the entire structure was watertight.

I. INTRODUCTION

Autonomous Underwater Vehicles (AUV) are robots that are designed and programmed to be self-sufficient to perform various tasks pertaining to the needs to the user in a marine environment. A typical AUV takes information from devices sensing analog signals, such as pressure, temperature, and depth, and relays them to the central processing system to enable the AUV to make informed decisions such as the detection and retrieval of objects, and avoidance of obstacles. The design and development of AUVs allows several engineering disciplines to collaborate, share, and build upon various experiences, thus the inception of the Texas A&M (TAMU) Women in Engineering (WE) AUV team, also known as Robotic Engineering Aggie Females (REAF),

The purpose of the formation of REAF was not only to compete in the annual RoboSub Competition but also to provide women in the College of Engineering at Texas A&M University with an opportunity to develop engineering and leadership skills as a part of a supportive team.

Over the past two years, the team has doubled in size and grown more sophisticated with the design of its AUV, named Ula. Last year, being our first time in the competition, the team's goal was to make it past the qualifying round, which they did. This year, drawing on the many experiences from RoboSub 2016, Ula has been redesigned in order to complete more tasks at the competition. In order to achieve this, the team was divided into three sub teams: Electrical, Programming, and Mechanical, which was further divided into smaller subgroups in order to meet the objective of why the team was formed, *i.e.*, to provide the opportunity for team members to gain technical skills. This division of tasks is shown in Fig. 1. Electrical team was divided into the data and power groups. The data group was responsible for communication between the Arduino and the sensors and thrusters, and power group was responsible for the design and fabrication of the AUV efficient power distribution system. The Programming team was divided into image processing group, who were responsible for the capture and processing of camera images, and the thruster control group who were responsible for the control of the thrusters based on the different outputs of the sensors in Ula. The mechanical team was divided into the mechanisms group and the structure group. The mechanisms group designed the various procedures that would enable the AUV to complete additional tasks such as marble dropping, while the structure group designed a compact and streamlined AUV.

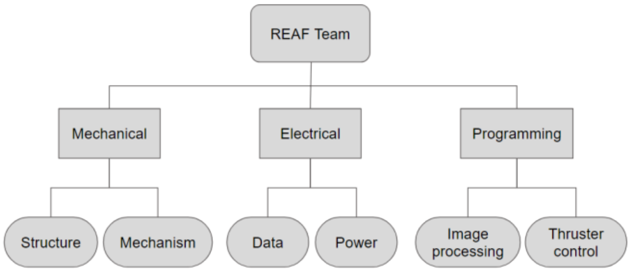

Fig. 1. REAF team structure

This year, the goal of the team is to draw on previous year's experiences, redesign, and develop an AUV that completes the obstacle course. This technical report is divided into five sections: Section II presents the team's design strategy; section III describes the AUV design; section IV presents some experimental results; and conclusions are drawn in section V.

II. DESIGN STRATEGY

Based on last year's experiences and inspirations from other teams, this year the team decided to do a complete redesign of the AUV, retaining only the previous sensors and thrusters. The mechanical structure was completely redesigned to be more hydrodynamic, as well as easy disassembly and reassembly when a component needs to be retrieved or repaired. The electrical design changed to accommodate higher levels of power and the use of more batteries. The array of microcontrollers that were used last year was completely substituted for a full computer with an increased amount of Random Access Memory (RAM) in order to fully implement the image processing algorithms.

III. VEHICLE DESIGN

This section gives an overview of the AUV's mechanical, electrical, and programming design and implementation.

A. Mechanical Design

The vehicle design was first inspired by drawing on previous team experiences with autonomously operated vehicles, as well as general ideas for the successful completion of specified functionalities. In the past, the team experimented with a face-sealed end-cap for the primary housing module and a rectangular-shaped chassis to house the electrical components, which created significant challenges.

Upon research and collaboration with professors and professionals, the overall design was reconfigured to be more hydrodynamic and for the internal components to be more accessible. The hydrodynamic portion of the vehicle involved reducing the surface area perpendicular to the direction of the flow of water and the rounding of the frame corners to allow the water flow over the vehicle to be smoother [1]. The use of a different type of end-cap mechanism created a similar and more time-efficient method of electrical components access through the endcap.

The physical design of the vehicle evolved significantly throughout the designing process using physical sketches to Computer-Aided Design (CAD) software. The primary objective was to create a vehicle that could be easily modified, as well as possess the ability to effortlessly access the electrical components housed within when necessary.

At various stages throughout the design process the mechanical team had to present the designs to groups of professors, professionals, and teammates from the other sub teams. This allowed for an overall look at the design and solicitation of feedback. Fig. 2 shows the CAD rendering of the mechanical structure

1) Buoyancy of the Vehicle

In order to ensure the stability and neutral buoyancy of the vehicle, buoyancy mathematical calculations were performed. The two components that generated positive buoyancy were the primary housing module which covered a volume of liquid displaced of approximately 0.03018 m^3 and the auxiliary housing module comprising of 0.003578 m^3. In total, the vehicle produced a buoyant force of 331.03 N which required a counter mass of 33.76 kg to achieve neutral buoyancy. The rest of the components in the vehicle represented a source of weight to be able to balance the buoyant force.

2) Chassis

The vehicle features an external chassis as a means of securing all mechanical components. The chassis was made from a mixture of non-flexible electrical metallic tubing (EMT) steel and aluminum alloy 6061 and could easily be separated from the main hull, which allowed work to be done on the actuators and internal components simultaneously. The circular rings included a groove that fit into a corresponding tongue on the main vehicle. This attribute ensured that the hull did not slip from the frame during operation. Hollow open-ended EMT was chosen rather than its sealed counterpart in order to allow water to flow through the chassis and decrease the amount of trapped air. The rigid nature of the chassis facilitated the displacement and deployment of the AUV.

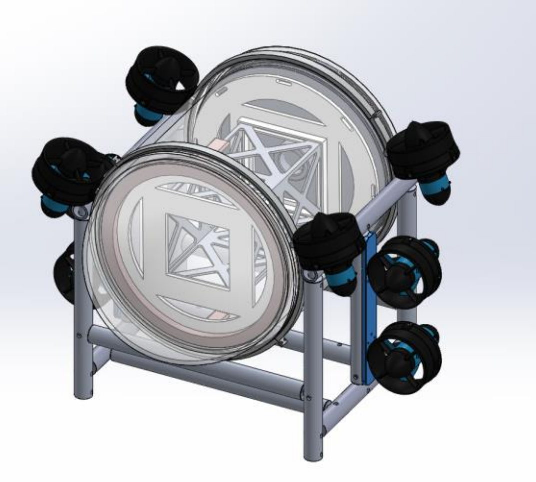

Fig. 2. CAD rendering of mechanical structure.

3) Watertight Vs. Waterproof

One of the utmost design concerns when constructing an AUV was keeping the interior of the vessel free of water. In everyday terms, watertight and waterproof can be used interchangeably, but this was not the case when it came to the construction of AUV's and other marine structures. When purchasing materials and designing components, it was important to note that waterproof referred to the majority of water being kept out of the area being protected, while watertight ensures that no water at all was able to enter the area. When dealing with sensitive electronics and sensors, it is critical that all seals and casings be watertight.

4) Primary Housing Module

In order to improve the AUV's hydrodynamic performance from last year, the shape of the hull was modified from a double flat faced cylindrical compartment to a dome front faced cylinder. The final materials selected for the main hull were selected to be clear PVC for the cylindrical body and polycarbonate for the front dome. These materials were determined to be the most cost effective, lightweight, and durable for the AUV. The dome and body are epoxied and permanently fixed together. For the endcap, a double O-ring bore seal was designed with the intentions of being easily removable yet dependable for water tightness. The endcap was fabricated from Aluminum 6061 alloy. The endcap was sealed by four rotating locks that fit into an indention and thus holding the endcap in place through tension. In order to maintain atmospheric pressure within the hull, a pressure relief, was installed in the middle. The endcap is the only removable section of the AUV through which all the wires pass via Blue Robotics cable penetrators and SubConn connectors. Fig. 3 illustrates the endcap design.

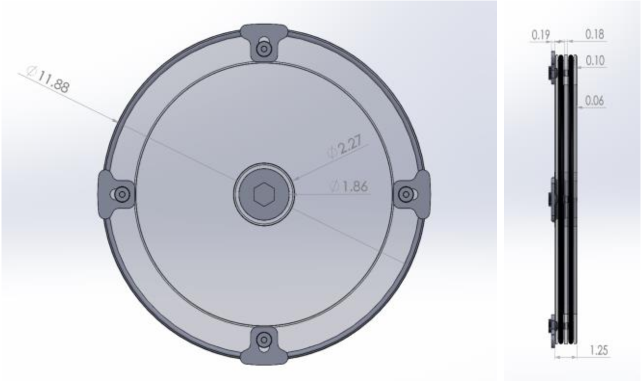

Fig. 3. Easily removable endcap design

5) *Auxiliary Housing Module*

Noticing a possible safety concern when storing batteries in the primary housing module, two watertight, polycarbonate containers were utilized for battery housing. The housing containers have a similar sealing method to the primary housing module, where they allowed access within by a removable lid that can be securely screwed onto a silicon rubber O-ring to ensure water tightness. Having an individual volume of about 109.16 cubic inches, the containers were stored underneath the electrical housing container, where they were attached to the frame cross-sectional bars with Velcro. Wires that penetrate the containers and the endcap were used for the power connection.

6) *Actuators*

i) *Thrusters*

The AUV used eight Blue Robotics T200 Thrusters strategically placed on the frame of the vehicle to enable specific movements underwater. Four of these thrusters were attached to the rings of the frame at the vehicle corners, 10 degrees above the horizontal, with the purpose of directing the cone-shaped water flow away from the sides of the vehicle to maximize efficiency in the up and down direction. The other four were placed in pairs along the left and right side of the frame for forwards and backwards movement, preventing the need to operate at full power being that there are two thrusters attached at each side. Fig. 4 shows the frame and thruster placement.

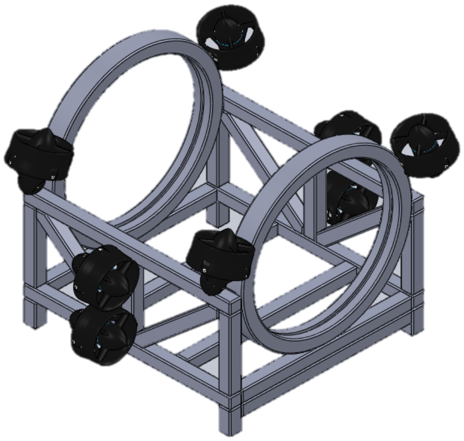

Fig. 4. Thruster placement

ii) *Gripper*

Biped Hand “A” from the humanoid Biped Pete assembly [2] acted as the gripper mechanism for the AUV. It was powered by two servo motors: the HS-422 servo controlled the movement of the “fingers” while the HS-485 servo controlled the movement of the “wrist.” These two servos allowed the gripper to have two total degrees of freedom to complete as many tasks as possible. The gripper was also centrally located on a pegboard on the underside of the AUV. This served to stabilize the center of gravity of the AUV so that it would remain upright during submersion. This placement also gave better judgment as to the distance the AUV needed to travel once an intended target came into camera view. In other words, if the visual processor located at the front of the AUV detected an object that needed to be grabbed, the AUV would move approximately half its length so that the gripper would be directly above the targeted object, thus improving gripper accuracy.

iii) *Marker Dropper*

The team developed a marble dropper mechanism, shown in Fig. 5, that is able to drop a maximum of two markers into two different bins. The marker dropper is powered by a 360-degree HS-422 servo. Within the marble dropper mechanism, there are three separate compartments. In two of the compartments, a single ½ inch steel marble is placed into each, and the final compartment will be completely empty, serving as the initial configuration of the marble dropper. The mechanism uses the servo to rotate a fan-like apparatus 90 degrees, and pushes each marble out a ¾ inch hole. The marker dropper is attached to a thin, metal, pegboard located on the bottom of the AUV. The marble dropper mechanism was entirely 3D printed out of ABS plastic material.

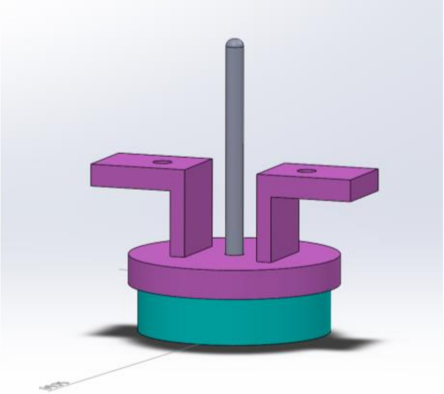

Fig. 5. Upper part of the marker dropper mechanism

iv) *Torpedo Launcher*

Another task required the vehicle to shoot two torpedoes at a designated target. To meet this requirement, the team designed and built two spring-loaded torpedo assemblies. The torpedo and spring each slide onto a ⅛” steel rod, and the spring is held in its compressed position by a pin through the rod. As image processing aligns the vehicle in front of the target, the 360-degree HS-422 servo, which is attached to the pin, powers up. This movement removes the pin from the rod, and allows the spring to decompress, pushing the torpedo off the rod in the direction of the target. The torpedoes and casing are 3D printed out of ABS material. Fig. 6 shows the CAD drawing of the torpedo.

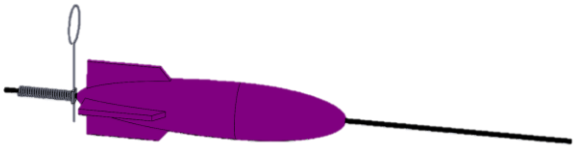

Fig. 6. Torpedo propelled forward by spring

B. Electrical Design

The electrical portion of the AUV handles all components that deal with power and data transfer. Last year the AUV was controlled using an array of Raspberry Pi's and Arduino Uno's. This year the main computer was ungraded to an Intel NUC and the thruster and sensor interface has been modified to an Arduino Mega.

1) Power

i) Batteries

Four 14.8 V 10000mAh Lithium-ion batteries provide power to the AUV. Lithium-ion batteries were chosen because of their reasonable cost, energy density, and size [3]. 14.8 V was the selected voltage because it was the most commonly found voltage that was higher than the maximum required voltage for any of the electrical components. The batteries were placed in parallel to double the amount of available current that could be supplied to the thrusters.

ii) Power Distribution System

The power distribution system has been expanded from last year in order to support the increase in the number of components. The system consists of two segments: the main system and the thruster system, in order to keep noise from the thruster out of the main system.

The thruster power distribution system powers the eight thrusters. This segment uses two batteries, a voltage regulator, and terminal block to distribute power to the thrusters. The voltage regulator keeps the voltage steady and provides over-current and short circuit protection. The terminal blocks equally distribute the power among the thrusters.

The main power distribution system powers all components besides the thrusters. This segment consists of 2 batteries, an ATX power supply, a custom PCB, and a custom Arduino mega shield. The ATX power supply provides steady voltage rails to keep sensitive components from experience voltage drops or spikes.

iii) Custom PCB

The custom PCB, shown in Fig. 7, uses the 5 V and 12 V volt rails to distribute power to the components using the proper connectors. The PCB supports three SS aqua cams, one US300 pressure sensor, the Arduino mega shield, and the Intel NUC. The PCB has extra connectors in case any components need to be added.

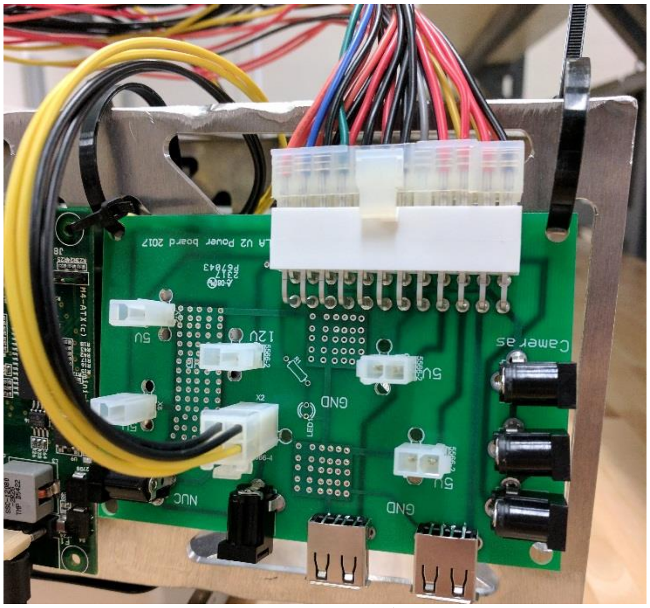

Fig. 7. Custom printed circuit board for power distribution

2) Control Systems

The AUV has two types of devices that need to be controlled, thrusters and servos. The Blue Robotics T200 thrusters and the various types of servos being used are both controlled using pulse width modulation (PWM). PWM works by controlling the width of the "on" part of the signal. In the case of the thrusters, the longer the "on" signal the faster the thruster will go. Inversely, the "on" width can be adjusted to make the thruster rotate at a slower speed.

The thrusters use an AfroESC 30A (electronic speed controller) to control the speed of the thrusters using the PWM signal. To control all of the devices of the AUV, 13 separate PWM generators are needed. An Arduino Mega was chosen for three key reasons. It is easy to use and there is a vast open source library of code to work with. It also has 15 PWM output pins. The servo code has been calibrated to not exceed the servo's maximum rotation capabilities.

The Arduino Mega is programmed using the Arduino C language. The Arduino Mega is used to receive the data from the pressure sensor as an analog input, convert it to a digital value and relay it back to the NUC using the serial interface. The Arduino Mega is programmed using the built in Arduino language and integrated development environment. The data flow diagram showing how the various electrical components communicate is presented in Fig. 8.

3) Sensors

The AUV utilizes a Specialties US300 pressure sensor [4] to measure the depth of the vehicle in the water. This year the team was able to implement the SS Aqua Cams that were purchased last year. The biggest challenged that was faced was getting the analog cameras to convert to a digital signal so that image processing could be used. This task was accomplished using an ION Video 2 PC Analog-To-Digital Video Converter [5].

The AUV uses a VectorNav VN-100 that was donated to us by VectorNav to gather information about the vehicle's attitude and heading. The VN-100 is a high-performance Inertial Measurement Unit (IMU) and AHRS. It uses the latest solidstate Micro-Electro-Mechanical Systems (MEMS) sensor technology. It was selected because it includes a set of 3-axis gyroscopes, 3-axis accelerometers, 3-axis magnetometers, a barometric pressure sensor, and a 32-bit processor [6].

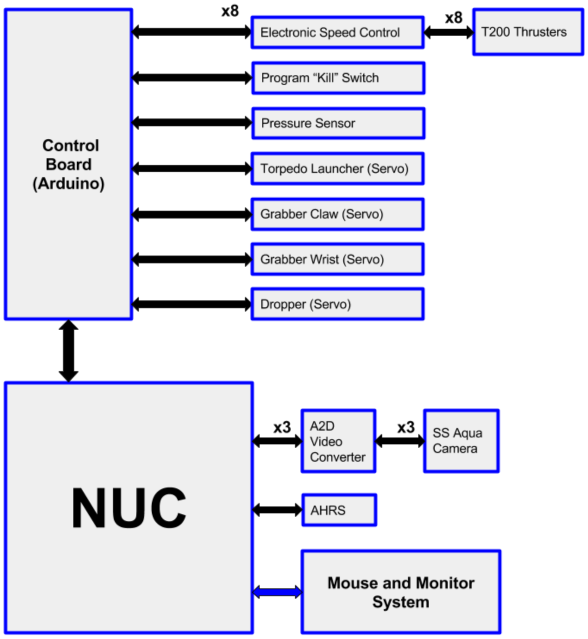

Fig. 8. Data flow diagram

4) *Kill Switch*

As dictated in the rules of the competition, AUV has a kill switch that cuts power to the thrusters. Last year the kill switch was done in a way that cut power to all parts of the AUV, including the computer. Each time the AUV was launched during a run at competition, the team had to wait 3 minutes for the Raspberry Pi to boot up. This wait time cut in half the number of runs the AUV could make while in the arena. This year the team has equipped the AUV with two kill switches. One is thruster kill switch which immediately cuts power to the thrusters. The other is a mission kill switch that restarts the program that the AUV is running. At no point in time does the main computer ever lose power so the AUV has no boot up time between runs.

5) *Component Placement*

The components were arranged inside the hull to keep the center of gravity low and to minimize interference and noise with other electronic components. The interference is mainly a concern with the AHRS because it is such a sensitive piece of equipment. Fig. 9 shows the component placement.

6) *Connectors*

A combination of SubConn connectors and Blue Robotics cable penetrators were used to pass wires from outside the hull to the inside. Previously, the team had used all Blue Robotics cable penetrators because of their low cost. This year the SubConn connectors were added to reduce the number of holes that had to be drilled into the endcap.

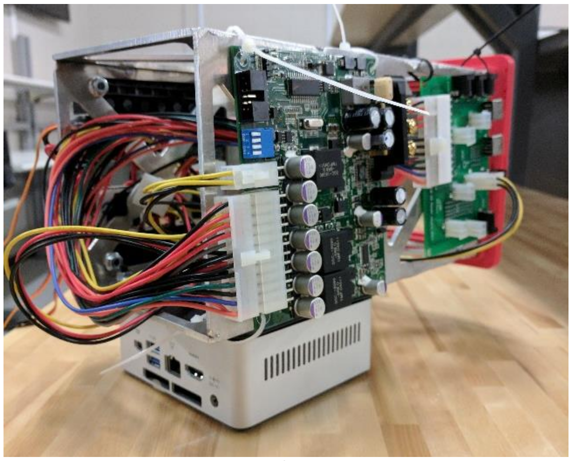

Fig. 9. Component placement allows for bulkier wires to pass through the center of structure.

C. *Programming Design*

A significant portion of the code coordinates the communication between the main computer, the sensors, the cameras, and the thrusters. The main computer - an Intel NUC - and an Arduino Mega communicate using a serial interface. Hardware constraints dictate us to connect the pressure sensor and the thrusters to the Arduino Mega. Data from the pressure sensor and the thrusters are extracted by the Arduino Mega and sent to the NUC. All other sensors and cameras are connected directly to the NUC. At the beginning of the main program on the NUC, separate threads are created, each gathering data from a different device or sending thruster commands to the Mega.

Once the data is gathered in the main program, each sensor data is evaluated to determine any necessary changes to functionality of the thrusters. For example, if the orientation data from the AHRS shows that the AUV is angled too far in one direction and may be about to flip upside down, the side thrusters are turned on in a way that corrects back to the expected orientation. Likewise, the pressure sensor is used to detect the depth of the AUV in the water. If the AUV is about to accidently breach the surface, the up/down thrusters are immediately turned on to force the AUV back down. The data from the thrusters themselves are the most crucial because they reveal whether or not the thrusters themselves are about to overheat, in which case the thrusters are all turned completely off. Fig. 10 shows the overall program flow chart.

1) *Thruster Motion Control*

Using the data gathered from the cameras and the current positioning of the AUV in space, the AUV calculates the most direct path to the object of interest in the camera frame. This path is then reduced to a unit vector in the direction that the AUV needs to travel based on the distance to the object calculated through the image processing [7], [8]. The AUV then uses a control and feedback loop to align its heading with the correct path, turning the thrusters on and off to control the surge, heave, and sway of the AUV [9].

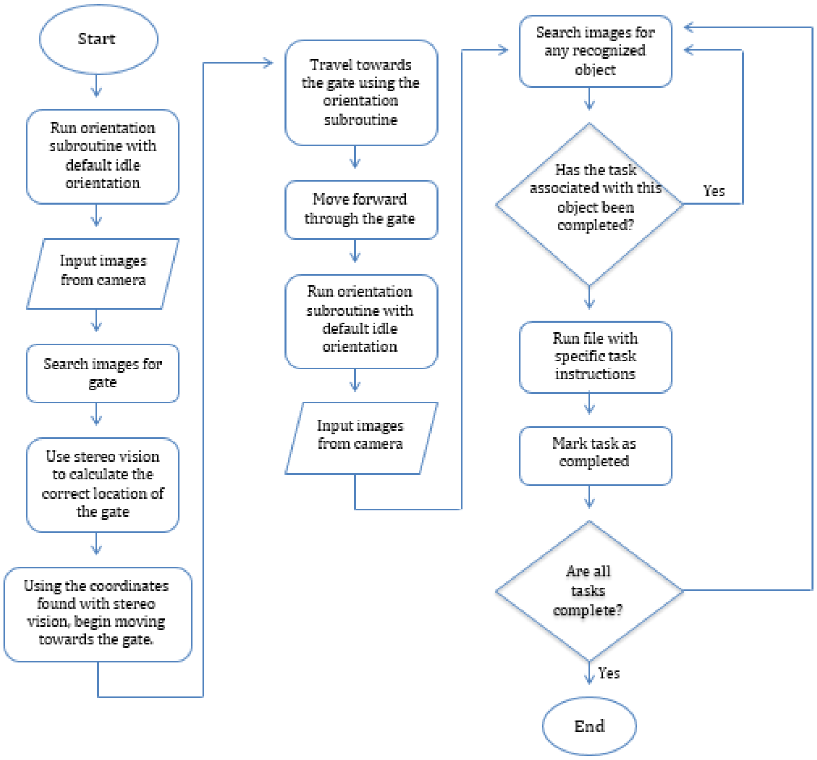

Fig. 10. The overall program logic dictates what should executed next in the program.

2) *Image Processing*

i) Image Detection

To complete obstacles, the AUV will need to detect images using computer vision. In order to do this, three approaches are being considered: background subtraction, template matching, and SURF/SIFT algorithms. Fig. 11 shows an object tracking scenario.

Background subtraction involves extracting an image's foreground for further processing, and is most useful when the background is static [10]. The background for the rear-facing camera features the bottom of the pool which remains fairly consistent throughout the shallow end of the pool. As such, this approach would be effective for the line-following task.

Template matching is a technique that identifies parts of an image that match with an existing template image. This method would be useful for following a line that branches off or curves, as well as identifying markers for the various obstacles throughout the pool. Eigenspaces can be implemented to account for different conditions such as perspective, illumination, and color contrast that will vary within the images [11].

Speeded Up Robust Features (SURF) and Scale-Invariant Feature Transform (SIFT) are based on the same principles, but execute each step differently. The algorithms involve detecting the image, providing a description of an image feature, and comparing the descriptors obtained from different images. Analysis has shown that SURF is three times faster than SIFT with comparable performance [12]. SURF and SIFT can handle images that blur or rotate, making them ideal for the front cameras that will experience motion blur as the robot traverses the pool.

ii) Stereovision

Stereovision is the process of creating 3D images from two or more digital images obtained from a series of cameras. We are using two front-facing cameras to obtain different views of the field and these images are compiled together to form a more accurate 3D representation of the field which helps us get more information about the depth of the plane. Stereovision is essential to estimate the location of objects [13].

iii) Kalman Filters

The task of tracking moving objects in a dynamic background proves to be complex due to change in orientation of the object, partial and complete object occlusion, varying lighting conditions, camera motion and unwanted noise added to the camera feed. The objective of tracking an object for our

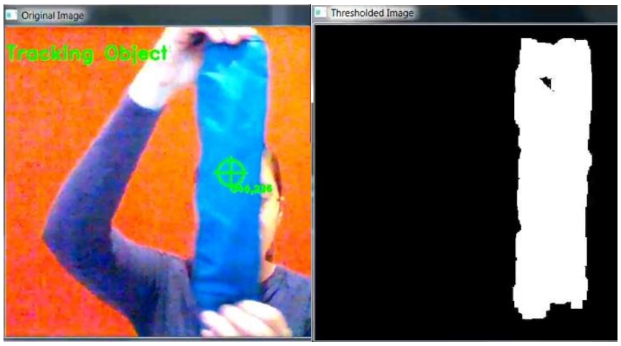

Fig. 11. Object color tracking allows the AUV to complete some of the basic tasks for competition.

AUV is accomplished by deploying the use of Kalman filters. The Kalman filter [14] provides a recursive solution to predict the state of the object from the past values and noisy measurement data. The Kalman filter can get close to accurate predictions after few iterations of its prediction and update steps.

In our algorithm, the Kalman filter also tries to adjust for the movement of the camera. This adjustment can be done by increasing the dimensions of the state variable to compensate the image frame positions and velocity with respect to the object or it can be done by adding the velocity of the camera to the kinematic equations incorporated to predict the future location of the object. In this way, Kalman filter is used for image stabilization.

IV. EXPERIMENTAL RESULTS

As of the submission of this paper, the complete AUV has not been tested in water yet. However, the mechanical structure without the electronics has been placed in water to determine if it is truly watertight. The electrical system has also been individually tested to estimate expected performance. Preliminary calculations have shown that the AUV will have a minimum runtime of 25 minutes if all 8 thrusters are running at top speed. This is more than the expected run time of each vehicle listed in the competition manual of 15 minutes. Experimental runtime has not been found yet.

V. CONCLUSION

This report has detailed the design and implementation of the TAMU WE autonomous underwater vehicle that will be competing in the RoboSub 2017 competition. Drawing upon last years' experience, the three subdivisions of the redesigned AUV, *i.e.*, mechanical, electrical, and programming has been explained and elaborated upon. The team continues to improve upon its knowledge in the design and development of AUVs and looks forward to advancing its design in the near future.

VI. ACKNOWLEDGMENTS

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