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MARV: Marine Autonomous Research Vessel

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SANTA CLARA UNIVERSITY

Departments of Mechanical and Electrical Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Drew Azevedo, Sam Bertram, Gregorio Del Vecchio, Ben Hopner

ENTITLED

MARV:
Marine Autonomous Research Vessel

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

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Dr. Christopher Kitts – Faculty Advisor date

June 8th, 2016
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MARV:
Marine Autonomous Research Vessel

By

Drew Azevedo, Sam Bertram, Gregorio DelVecchio, Ben Hopner

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical and Electrical Engineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering
Bachelor of Science in Electrical Engineering

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Santa Clara University
2016

ABSTRACT

Conducting hydrologic research in remote areas is currently performed manually, making it a labor intensive and inaccurate solution. Due to the size, weight, and cost of automated solutions on the market today, a need has arisen for a low cost, highly portable, autonomous solution. Working closely with Santa Clara University's Robotics Systems Lab (RSL), our team has developed a low cost, highly portable autonomous marine research vessel named MARV (Marine Autonomous Research Vessel). It is an autonomous surface platform where scientists outfit the vessel with their own data acquisition equipment. The mechanical chassis is collapsible for modes of remote transportation (i.e. helicopter, small trucks, backpacking). With a final weight of 25 kilograms, material cost of $4,482, and a cross track error of ±1 meter, we have successfully designed and manufactured low cost, highly portable autonomous solution. However, MARV does not operate on an adaptive navigation system. Further developments such as object avoidance and depth control would result in a fully autonomous marine platform.

Acknowledgements

The MARV design team would like to acknowledge the following individuals and institutions for providing resources and expertise that led to the success of MARV. Because of this support, we were able to achieve much more than we had initially imagined.

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- Dr. Christopher Kitts
- Santa Clara University’s Robotics Systems Laboratory
- University of Alaska, Fairbanks
- Miller Center for Social Entrepreneurship
- Jeff Ota (Intel Corporation)
- Addison Fattor and Ethan Head

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1.0 Introduction

Lakes and ponds are major features in the Arctic landscape, and span a diverse range of environmental conditions–from dilute, glacier-fed meltwaters to nutrient-rich tundra ponds and perennially ice-capped, stratified lakes with anoxic bottom waters [2]. Progressively warmer climates have led to arctic environments where these lakes and ponds are ever more present. Many different research institutions are currently interested in conducting research in and on these unique environmental features. However, the current data collection equipment available for research use is not adequately serving the needs of scientists. The goal of project MARV was to better understand these needs and design a unique solution to address them.

1.1 Current Data Collection Pain Points

Conducting research in remote regions, such as the Arctic, is severely hindered by the equipment that can be transported there. In many instances, equipment is flown in by helicopter and then hiked to the area of interest on the backs of the scientists. In rare cases, inflatable boats are brought to these remote locations. These large and cumbersome vessels must be stored at the closest permanent research facility. In almost all cases, the data is collected manually.

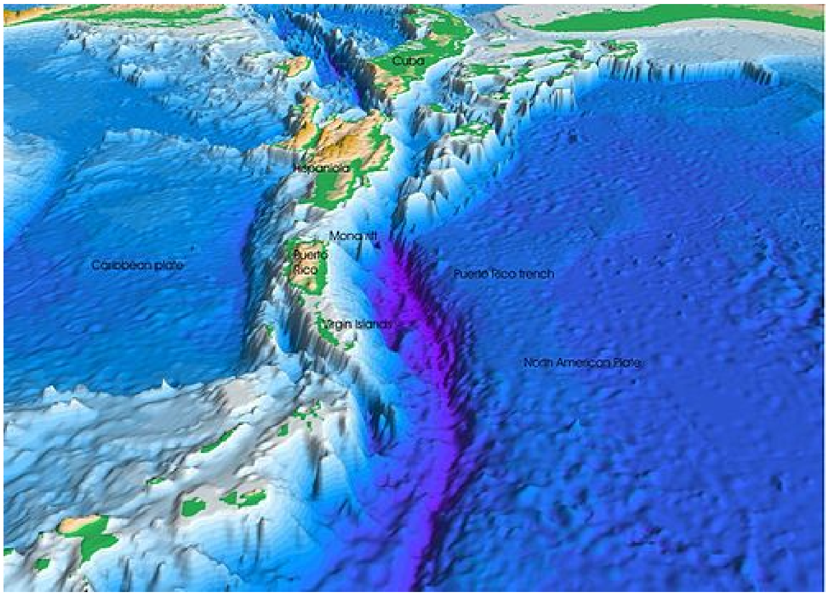


Figure 1: Example bathymetric map.
(Source: Wikipedia)

Manual data acquisition is not only labor intensive and time consuming, it is also inaccurate and difficult to repeat. The inaccuracy comes from the geographical referencing of the collected data points. A typical output of collected data is a bathymetric map of the body of water–which is a 3-dimensional mapping of the underwater topography. A bathymetric map of an underwater volcano is displayed in Figure 1. Maps like these cannot be created with manual data collection methods. Along with the data the scientists gather, they can have a visual representation of that data and have it geographically referenced on the bathymetric map.

1.2 Previous Solutions: Advantages and Disadvantages

Santa Clara University's Robotic Systems Lab (RSL) has worked on several projects that include innovative technology that can successfully assist navigation and collection of important data. SWATH (Small Waterplane Area Twin Hull) is a fully autonomous platform that is a result of over a decade of research. SWATH has successfully generated science-quality underwater mapping of various bodies of water [3, 5, 26]. Other projects, such as the SCOAP (Surveying Coastal Ocean Autonomous Profiler) of the University of Rhode Island and the autonomous Argo Profiling Float of UC San Diego, are similar to SWATH in size and functionality but they all are far too big to be transported efficiently [4, 5].

Drawbacks of SWATH, SCOAP and Argo*:*

- +750 lbs
- Require special modes of transportation
- Replacement parts must be custom made
- Not configurable

Other projects have been able to integrate a similar platform on a smaller frame significantly increasing the transportability of the system. The RSL has been a part of a research project involving the autonomous navigation of kayaks to collect general environmental gradients (water depth, water temperature, etc.); this has been a multi-stage program to help streamline water research and exploration [6]. Unfortunately, the system shared many of the drawbacks listed above, namely, ease of use and transportability. One project that aimed to solve the transportability issue was BathyBoat [7]. BathyBoat, a project that came from the University of Michigan, was autonomous, extremely transportable, and was outfitted to create bathymetric maps. However the project had a few drawbacks that were sufficient enough to eliminate it as an ideal candidate.

Figure 2: BathyBoat project completed by University of Michigan.
(Courtesy of Dr. Guy Meadows, Director of Univ. of Michigan's Marine Hydrodynamics Lab)

BathyBoat Drawbacks:

- Lacks ability to accommodate various research instruments
- Platform not easily modified for unique cases
- Reduced stability during rougher conditions

It can be seen that the BathyBoat project has addressed key design criteria that is valuable to the researchers. But the potential drawbacks listed above prove to be significant enough to hinder data collection due to its lack of vessel versatility for various research locations and conditions.

1.3 Project Goal

The goal of this project was to design, manufacture, and deploy a low cost, highly portable autonomous research platform. To achieve this; we designed and constructed a collapsible mechanical chassis, integrated an off-the-shelf autopilot, and mounted a sensor to prove configurability. The mechanical chassis is comprised of two rolled aluminium pontoons connected by a bridge. This bridge is made of 80/20 aluminum structural framing. To integrate the off-the-shelf autopilot, we had to ensure that the outputs were communicating with the electrical components. For example, the throttle output from the autopilot had to be interpreted by a DC motor driver as an PWM input, based on this PWM input the DC motor driver would output a calculated throttle voltage to the DC thrusters. A sonar was mounted on to the 80/20 bridge to demonstrate that arbitrary sensors can be integrated into the platform with ease. This was achieved by utilizing one of many 80/20 attachments available on the open market.

These efforts resulted in the Marine Autonomous Research Vessel, MARV. The collapsible aluminum chassis weighs 25 kilograms for ease of transport and high portability. The off-the-shelf autopilot was integrated successfully into the platform and had a resulting cross track error of ±1 meters. The mounted sonar sampled data successfully and was configured in any orientation desired. The final material costs of MARV totaled $4,482, significantly lower than current market solutions.

The contribution was adding another autonomous platform to the Robotics Systems Laboratory's existing fleet of surface vessels. MARV will serve as a highly configurable platform for masters students and PhD candidates to develop highly sophisticated adaptive navigation algorithms to drastically improve the navigation performance. MARV is also a platform that can be offered as a service to potential customers through the RSL. The RSL has a history of developing robots to aid and accelerate experiments in the scientific community. MARV is now part of that history.

2.0 System Description

This section discusses the various aspects of the design process and decision making regarding the inception of MARV. Areas like a system block diagram, mechanical breakdown, customer research, previous projects, and design of subsystems are considered to ensure MARV's proper performance. This section aims to give the reader an insight into key aspects of the design of MARV as well as discuss key differences between MARV and past projects.

2.1 MARV System Block Diagram

Figure 3 displays MARV's overall system block diagram of its main systems, as well as their corresponding subsystems. These main subsystems (i.e. the colored portions) work together constantly in order to provide MARV with the necessary functionality for successful operation. The main subsystems are the chassis, data collection, movement, navigation and power. Each of these main subsystems are composed of various components that allow the subsystem to interact with others seamlessly. Noted by connecting lines, each subsystem interacts with another in order to complete various tasks while the chassis subsystem embodies them all. One subsystem that doesn't have any direct connections to other subsystems is the onshore computer. It is illustrated in Figure 3 that the yellow, onshore computer, block is separate from the rest of the system. This is done intentionally to show that MARV can run a mission autonomously with no input from the onshore computer. The onshore computer can be used for vessel status updates or navigation data when needed. Each of the six blocks shown below have a specific purpose that is vital to successful operation of MARV.

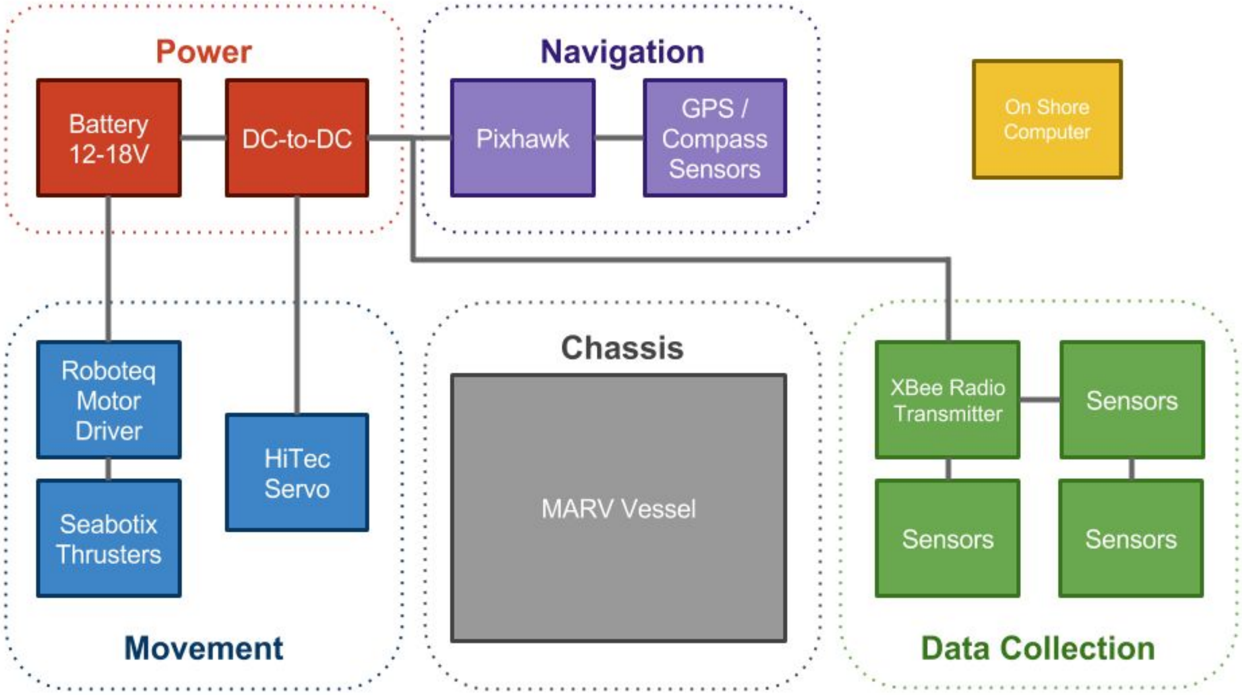


Figure 3: System block diagram of MARV's systems and subsystems.

2.2 Mechanical Breakdown

As seen in Figure 4 the mechanical assembly of MARV comprises of four main parts: right and left pontoon assemblies, the bridge assembly, and the steering column. It also has two off-the-shelf components: pelican case and the collapsible sonar. This is all part of the chassis block in the system block diagram that will be discussed in further detail in Chapter 4. In Figure 5 is the finalized MARV at the 2016 Senior Design Conference, mirroring the drawing in Figure 4.

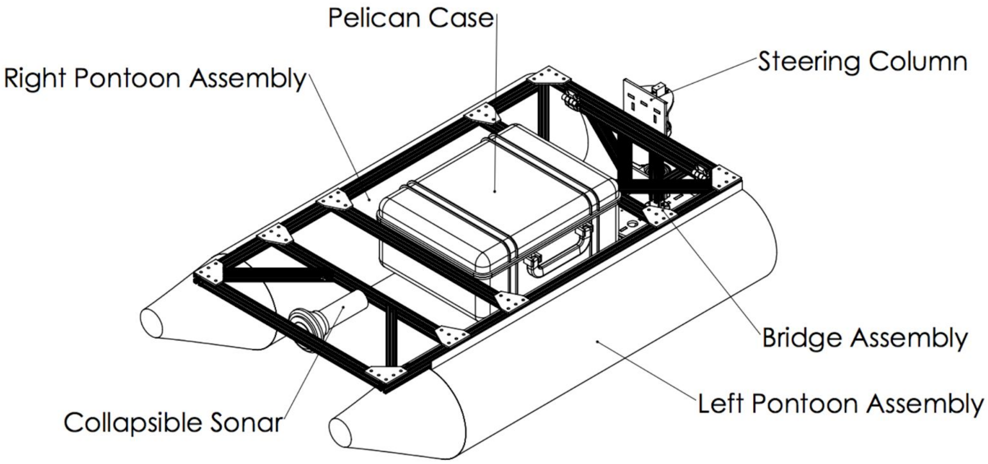


Figure 4: Mechanical breakdown of MARV.

Figure 5: Marine Autonomous Research Vessel at the 2016 Senior Design Conference.

2.3 Potential Customers

Institutions have expressed desire for a system such as MARV and they are listed as potential customers below. Figure 6 shows scientists from one of the potential customers, the University of Alaska Fairbanks. This is one of the environments in which MARV designed to operate. This particular picture is in the arctic circle in the summer months. Having these scientists available for interview by Team MARV was critical in understanding the problem at hand.

Figure 6: UAF Scientists in the Arctic Circle
(Courtesy of Dr. Geoff Wheat, Research Full Professor of University of Alaska Fairbanks)

Table 1: Customer data collected during MARV design process.

Organization	**Desires**
Robotic Systems Laboratory (RSL)	- Modular platform built from RSL lab-standard components - Deployable by any lab personnel - Platform to test cluster control algorithms
University of Alaska - Fairbanks (UAF)	- Operate in shallow waters - Operate in high-altitude environments - Able to fit in a helicopter cage
MBARI [24, 25] (Monterey Bay Aquarium Research Institute)	- Requires transportable platform for various research conditions - House interchange sensor packages
University of Portland (UP)	- Deploy in Lassen Volcanic National park - Study biological activity in geothermal vents - Withstand boiling environments
University of Central America (UCA)	- Map (Bathymetry) of the Lempa river - Sediment samples in Rio Lempa basin - Measure the effect of sediment build-up on water flow through the dam

2.4 Questions Used to Define Customer Needs

The following questions were directed specifically towards several of the aforementioned potential customers to define what they desire in an autonomous system like MARV. Paired with the design team's goals of system modularity and versatility, questions were generated to define design parameters. Our team believes there is great value in empathizing with the customer to fully establish and understand the need early on in the design process. The questions and corresponding answers are listed below.

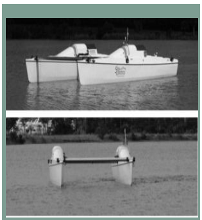
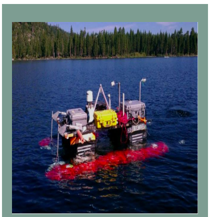
Table 2: Customer interview questions and responses.

Questions	Responses
What is the desired speed?	1 - 2 Meters/sec
What is the desired mission duration?	4 - 5 Hours
What is the total distance of data collection?	1 - 2 Kilometers
What is the minimum depth of the body of water where MARV will be deployed?	1 Meter
What is the desired weight of MARV?	50-60 kilograms
What absolute GPS accuracy is desired?	± 3 Meters
What file format would you like the data?	Excel or MATLAB
Would you like real time data streaming?	Not necessary
Where will MARV be deployed?	Thermogenic, Arctic, Rivers, Small Lakes (1km - 5km in diameter), Ponds (<1km in diameter), and Dams
What vehicles will MARV be transported in?	Helicopters, Planes, Vans, Trailers, Trucks
What would be an attractive price tag?	< $10,000

2.5 Competitive Analysis

There are a number of other vessels that have similar capabilities to what MARV aims to achieve. Learning from the positives and negatives of each of these vessels is vital to bypassing many unfavorable design decisions. Each individual project, listed in Table 3, successfully solves the problem at hand where it is desired to collect hydrological data using an autonomous research watercraft.

Table 3: Related projects that have similar functionalities to MARV

Description	 **SCOAP** [1]	 **BathyBoat** [2]	 **SWATH** [3]	 **Z-Boat** [4]	 **Heron** [5]
Autonomous	✓	✓	✓	✓	✓
High Stability	✓		✓		✓
Transportable		✓		✓	✓
Easy to Use				✓	✓
Rugged			✓	✓	✓
Baseline Cost	N/A	$4,500	~$10,000	$18,300	N/A
Customizable			✓		

Even though the projects listed above satisfy the design requirement of an autonomous research vessel, the individual projects fail to address all of the key design requirements set forth by customer data and design parameters. MARV needed to be easily transportable, easy to use, extremely transformable (modular), while being cost effective. To do this, an analysis of standard hulls was completed to ensure that the onboard hardware and sensors would be structurally sound as well as durably transportable to highly remote locations. The two hull configurations that were considered were the standard single hull setup and the standard pontoon setup. Both options are readily used throughout watercraft for general recreational as well as scientific usage. The following discusses the results from the hull configuration analysis:

- Single Hull Configuration:
    - The BathyBoat project uses a single hull; this does not promote stability during operation in harsh environments. It is also not possible to interchange sensor packages due to its enclosed design. This showed that a single hull configuration would not be an acceptable design for MARV.
- Traditional Implementation of Large Pontoons:
    - SWATH and SCOAP hull designs prove to be very stable configurations for various conditions. However, the SWATH and SCOAP projects do not have a transportable hull, making them inadequate solution for the design parameters.

2.6 System Environment

After the design considerations were defined and understood, MARV's system environment of how the vessel would interact with the end user and target location needed to be defined. Since MARV has the ability to be placed in a variety of remote locations, the same key actions must be constant during standard operation procedures regardless of the user. Figure 7 represents an example system environment that displays how MARV navigates along a path and interacts with the user.

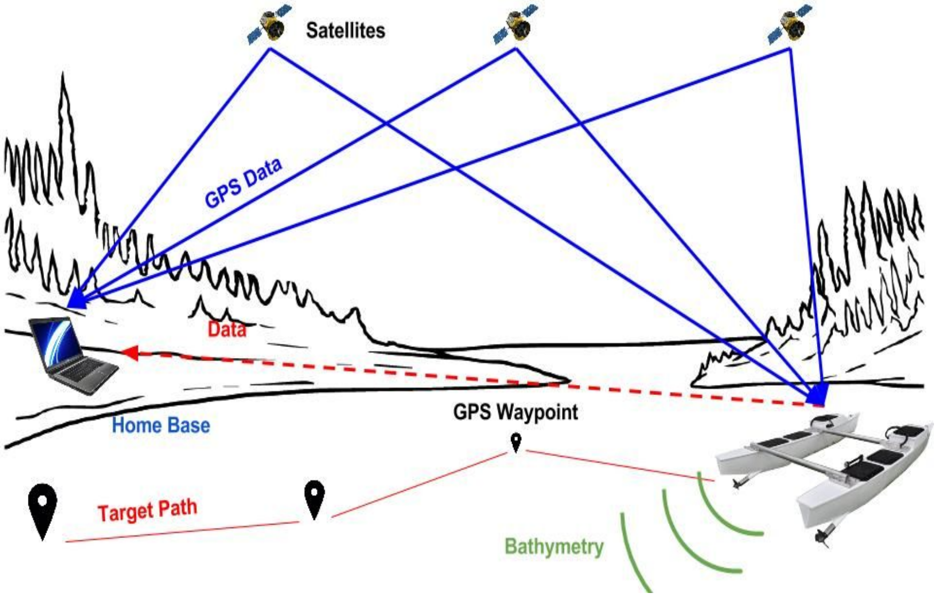


Figure 7: System environment sketch of MARV during operation and testing.

As seen in Figure 7, the system environment that MARV operates in requires significant communication between the vessel and the onshore computer. Once MARV has recognized that it has a route to follow, the vessel begins following the predetermined path and relays data via telemetry back home to the user. The direction in which MARV travels is determined by recognizing the path between two waypoints. This path is the direction and location MARV wishes to travel during its operation. At each waypoint, the onboard GPS recognizes whether or not the boat has reached the target point within a certain radius of accuracy and communicates the information back to the user. Simultaneously, sensor data is collected continuously during the mission via the attached on-board sensors. This process continues as MARV travels through its mission until it reaches its final waypoint and promptly returns to home.

2.7 System Requirements

Based on the feedback received from real world customers, competitor analysis, as well as our own goals for feasibility of project completion by the end of the term, we've developed the following list of required specs for MARV that we intend to achieve in our final design.

Table 4: Required Specifications for MARV

Specification:	Value:
Size and Weight	0.6 x 0.6 x 2.5m - 50kg
Precision Path Control	< 3 meters
Minimal User Involvement	autonomous navigation
Desired Cost	< $5,000

2.8 Component Breakdown and Hierarchies

The following table describes the component hierarchies designed based upon the customer interviews above. The components can be separated into five categories: Communication, Data Acquisition, Movement, & Chassis.

Table 5: List of component hierarchies decided by team.

Component Hierarchies	Reason for Importance
Communication	-
Telemetry Module	Bidirectional communication with ground control
MARV-to-Home	Relays vital data from MARV to home
Home-to-MARV	Gives MARV navigational commands
Data Acquisition	-
Sensors	Modularity to mount a variety of sensors
Movement	-
Navigation	-
GPS System	Essential to navigation accuracy
Onboard Compass	Provides heading accuracy
Power	-
Battery Capacity	Defines length of missions
Chassis	-
Motor Mount Design	Ensures safe motor operation
Design	Must hold all necessary components
Materials - Aluminum	Influences strength and weight of hull
Sensor Attachments	Must accept sensor attachments

2.9 Reflection on Customer Results:

The results of the customer analysis validate the concepts the team had originally determined. However, a number of extra constraints arose along with several other requirements that were not previously mentioned. Examples include:

- a sturdy hull that can withstand large temperature differentials
- stability in all water conditions
- depth-sensing navigation
- recessed thrusters.

The main request from all customers was modularity. The vessel **must** be able to incorporate **any** sensor package. Some sensors require contact with water, others do not. Another aspect that was not fully understood prior to customer interviews was the definition of portability. Since the system must be transported via helicopter and backpack, there is an added emphasis on portability and total weight of the vessel. Figure 8 shows that MARV can fit adequately into a helicopter cage without taking up too much room.

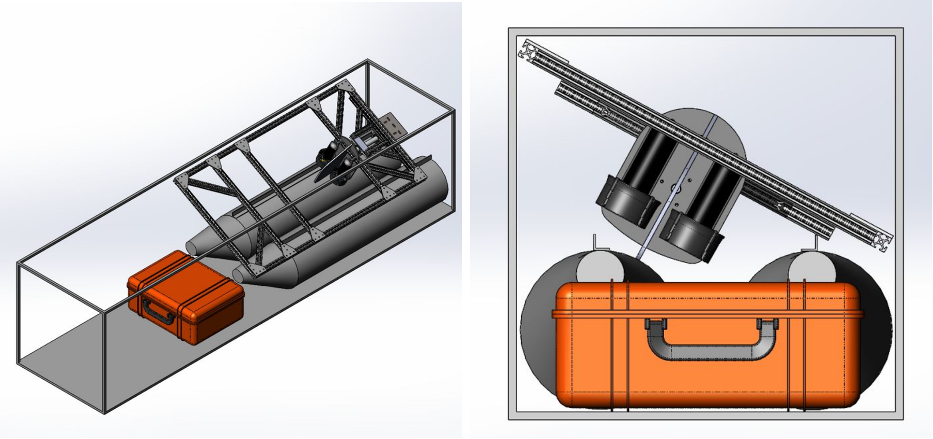


Figure 8: The isometric view (left) and front view (right) of MARV in the helicopter cage.

3.0 Project Management

3.1 Constraints

Our main constraint is the overall volume of the vessel. The vessel must be able to be transported via helicopter to an area of interest. There is a dedicated storage cage on the outside of the helicopter in which MARV could potentially be transported. The dimensions of this cage are 2ft x 2ft x 8ft. The vessel must be transported from the landing site of the helicopter to the area of interest by foot. Therefore, the weight restriction on MARV is a constraint that must be adhered to in the design. The team set a maximum weight of 50 kg (110 lbs) for the vessel. The ergonomics of the design also affects the transportability. The placement of handles and straps in which MARV is transported is critical, especially if transported over distances of a couple kilometers.

Since MARV targets non-technical users, it is critical that MARV is easy to operate. The software interface chosen is intuitive and mimics existing map interfaces such as Google Maps. Ardupilot's Mission Planner achieves this level of user experience. The hardware interface only has a few functionalities that require interaction from the user. These include: master on/off switch, manual override with RC transmitter, access to charge batteries, and the ability to exchange sensors on the sensor platform.

Power management for MARV is a direct result of the volume and weight constraint. The size of the battery affects the weight, volume, mission time, the number of components the system can accommodate, as well as the size of the body of water it can explore. The versatility of the vessel allows the user to add varying sizes of batteries depending on the conditions they wish to test in. This access to the electronics required the entire electronics network to be in an openable waterproof container. We chose to utilize the Pelican 1550 Protector Case to satisfy the constraint of waterproofing.

Navigation was the greatest difficulty for the project. Since navigational accuracy is vital for MARV's success, an autopilot module was purchased providing all of the functionality necessary for MARV. The module is 3D Robotic's PixHawk autopilot module for $200. This unit achieved the desired navigational accuracy for successful operation making it the ideal configuration for navigation.

3.2 Budget

The budget for this project was split into four separate categories: the hull, the system hardware, power management and local travel expenses. Most of the components used for the project were owned by the Robotic Systems Laboratory (i.e., thrusters, motor drivers, microprocessors, RC transceivers, autopilot, batteries, etc.) Our budget expenditure was directed towards prototyping costs and travel costs for field testing. The team designed the entire mechanical structure from 80/20 structural framing. 80/20 is one of the most widely distributed and readily available aluminum structural framing systems. It can be purchased from a plethora of online distributors.

The commonality of the structural framing made it possible to reduce costs of the system. This was the same for the 5052 aluminum sheeting used for pontoon construction. A more detailed budget and mechanical prototyping costs can be found in Appendix 4.

3.3 Timeline

The timeline was broken down by quarters over the course of the academic year. Fall quarter's focus was to prototype multiple hull designs. Once the team had decided on the final design, the construction of the design was to be completed by the end of Fall quarter. Winter quarter's focus was to integrate the 3DR autopilot, thrusters, and steering column for manual control. Spring quarter's focus was to have MARV run missions semi-autonomously, complete vigorous field testing, and to collect depth data to create a bathymetric map of our test lake. A more detailed timeline with major project milestones can be found in Appendix 2.

3.4 Design Process

MARV's design approach and decisions were heavily dictated by field testing. The team assumed early on in the project timeline that critical design flaws are often discovered in the field. Using the desired design criteria set forth by customer data and former low level RSL prototypes, key design considerations were discovered and features were prioritized based on customer and design team target goals. The use of field testing gave the team invaluable information regarding specific designs of subsystems on MARV and provided an opportunity to refine them. This was the primary iterative design process that was used in the project.

3.5 Risks and Mitigations

The purpose of this section is to address all safety risks and concerns that MARV presented to the design team and its users. There exists the potential for safety concerns in 4 particular areas: prototyping of the hull, testing and operation, storage, and transportation. Each safety review of the project aspects was aimed to address any safety concerns brought forth by the design team/users and provide procedures and safeguards to minimize potential hazards. A detailed explanation of each area can be seen in Appendix 5.

3.6 Team Management

The MARV design team consisted of an interdisciplinary engineering team where each individual possessed an expertise regarding one or more areas in engineering. Based off of these skillsets, the design team was assigned areas of the project to address how key considerations were dealt with and implemented for successful operation. As seen in Table 5, the design team members and their strengths are listed. The design team also had help from other members of the Robotic Systems Laboratory that provided key expertise in several crucial areas as well.

Table 6: List of team members and their strengths.

Team Member	Strength	Engineering Major
Drew Azevedo	Hull Design/Sensor Selection	Mechanical
Sam Bertram	System Architecture	Mechanical
Greg Del Vecchio	Electronics/Power Mgmt	Electrical
Ben Hopner	System Integration	Mechanical
Addison Fattor*	Software Support (Linux OS)	Computer
Ethan Head*	Software Support (Python)	Electrical/Computer

**Members of the RSL who have generously volunteered their time for the development of MARV*

3.6.1 Explicit Team Goals

In the summer of 2015, our team met frequently to decide unanimously on a project. The criteria that had to be satisfied: the project had to be feasible but academically rigorous, have a societal benefit, real world application and be field/mission ready, as well as providing an opportunity for us to develop skills that would help us in our professional careers. In order to successfully produce such a project, we had to improve our skills and knowledge of mechatronics, control systems, and the intricacies of the engineering design process. We were designing MARV to the customer's specifications such that there was an explicit definition of what the end product would be. Minimal experience in implementing design techniques in our engineering courses had not fully prepared us for a methodical, successful design process.

However, this was an invaluable opportunity for us as a team. We had first hand experience with working with a direct customer. As a team, we had decided to share leadership roles in different subsystems of the project, giving us all leadership experience and experience learning how to work effectively and efficiently in a team. We had also made it a priority to maintain a calm demeanor throughout the best and the worst times. When the project came to an end, our goal was to be able to present our project in such a fashion that it was entertaining, understandable for a diverse audience and technically developed. With this robust list of explicit team goals, we learned and gained invaluable skills, experiences, and opportunities from this project.

4.0 Mechanical Subsystem Breakdown

The mechanical components on MARV consist of: the pontoons, the bridge and the steering column assembly. The hull consists of left and right pontoons that are connected by the bridge. The steering column assembly consists of many parts, as can be seen in the Figure 9 below.

4.1 Mechanical Block Diagram

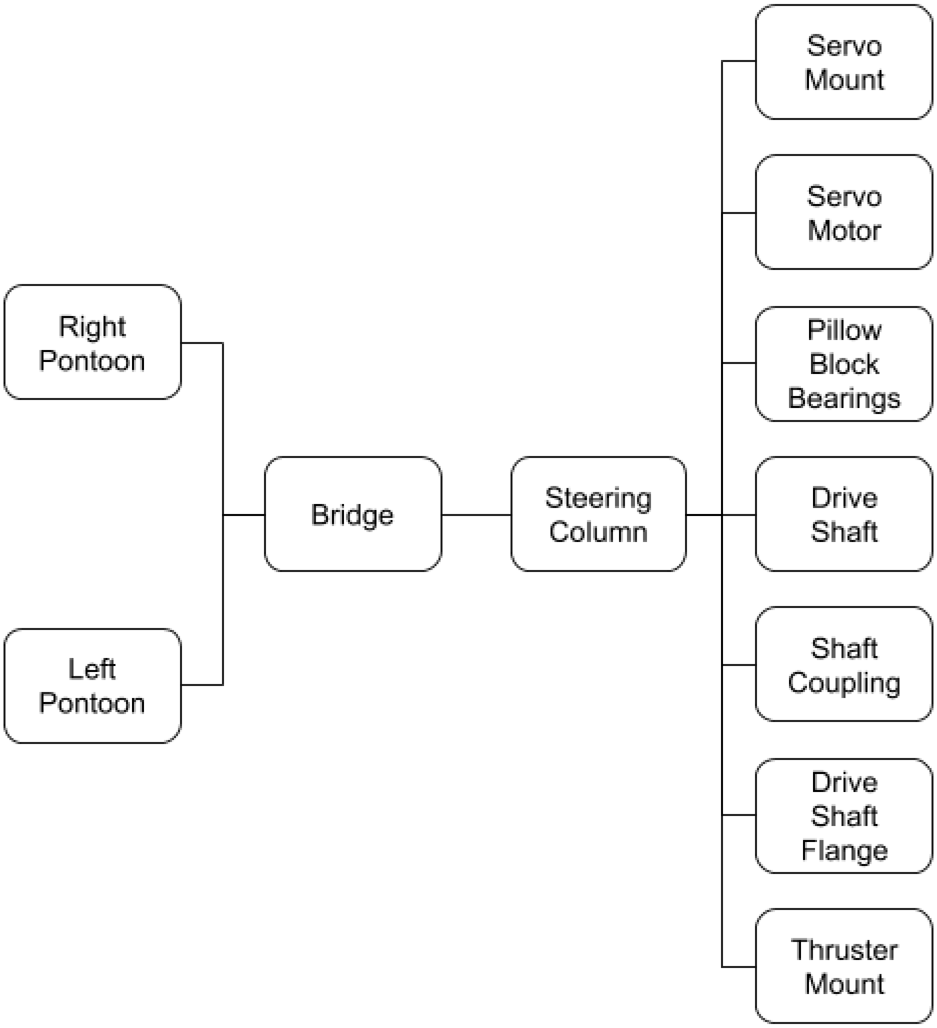


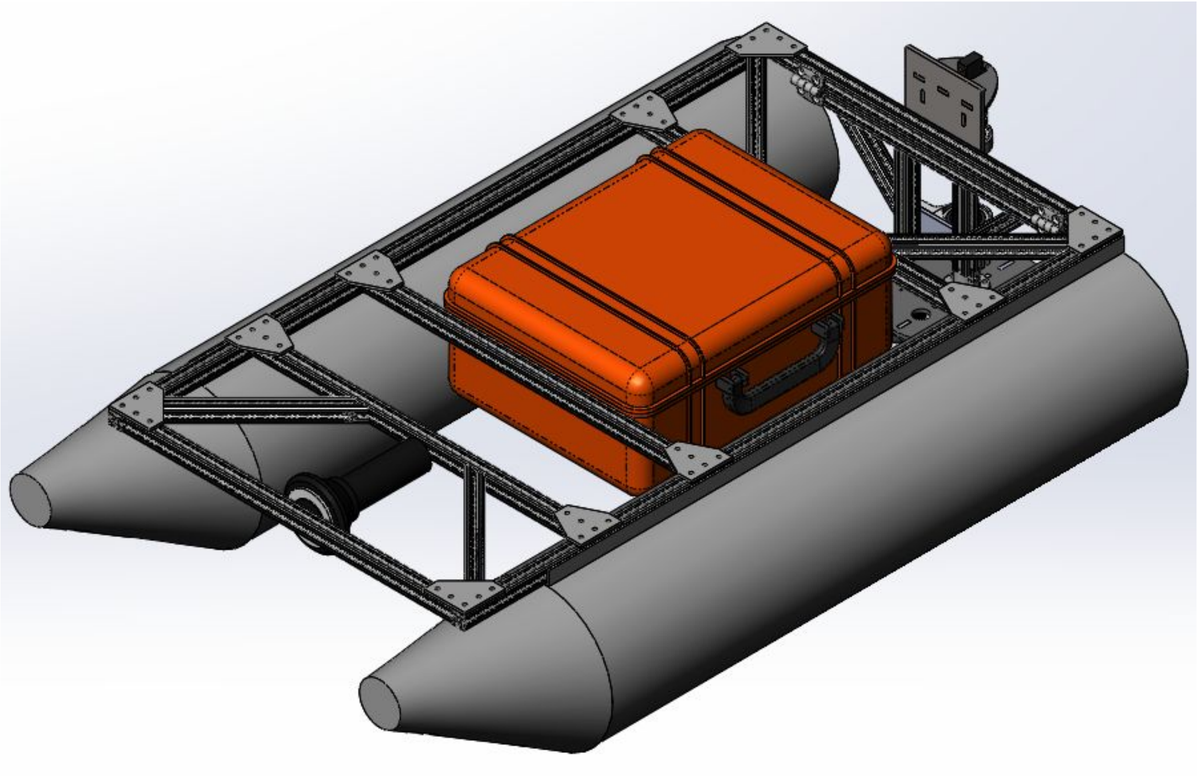
Figure 9: Mechanical Block Diagram of MARV.

4.2 Structural Design of MARV

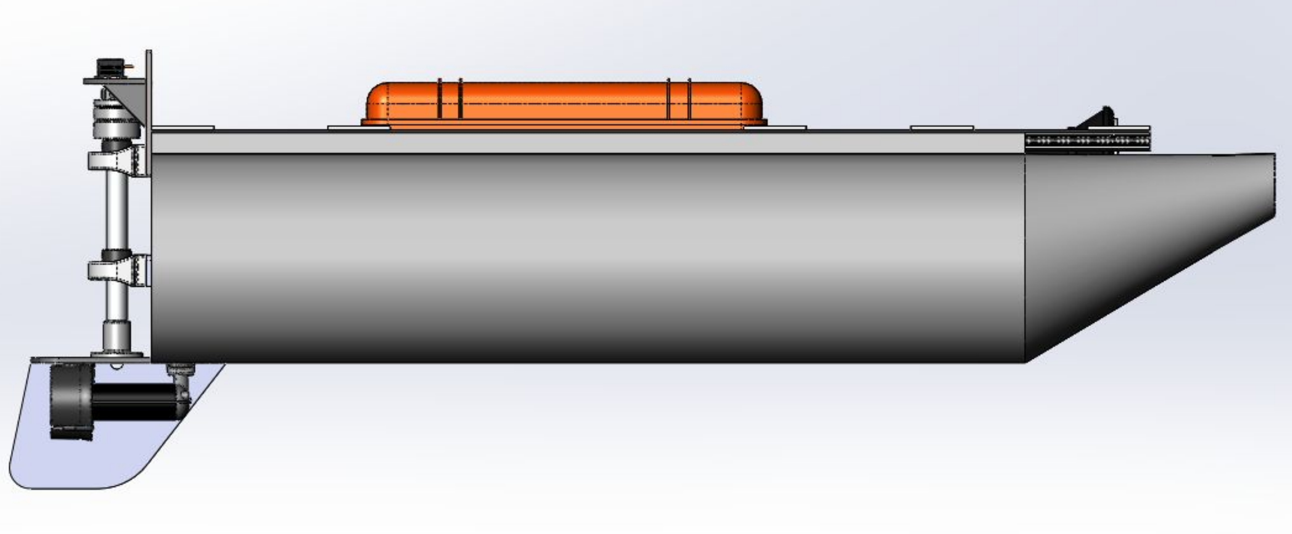
After many iterations in the design process, the following vessel became the main platform for the sensor packages and payload. Figures 10 and 11 display the chosen vessel configuration and the final prototype. As seen in Figure 10, the proposed design for MARV consists of two pontoons that are made out of 5052 marine aluminum at a thickness of 0.080”. This material was chosen because of its ability to be highly durable while remaining lightweight. The frame that connects the two pontoons (referred to as the “bridge”) is constructed from extruded aluminum

1" 80/20 framing. Our team chose to use this material because of its capacity to be customizable and its abundance within the marketplace. Many different attachments exist for the 80/20 framing which means consumers can purchase mounts or connectors to adapt the system to their specific application. As seen in Figure 11, many additional 80/20 cross members can be added as additional support mechanisms and attachment areas. All this provides modularity and customization capabilities to the vessel allowing it to be broken down and rebuilt with relative ease.

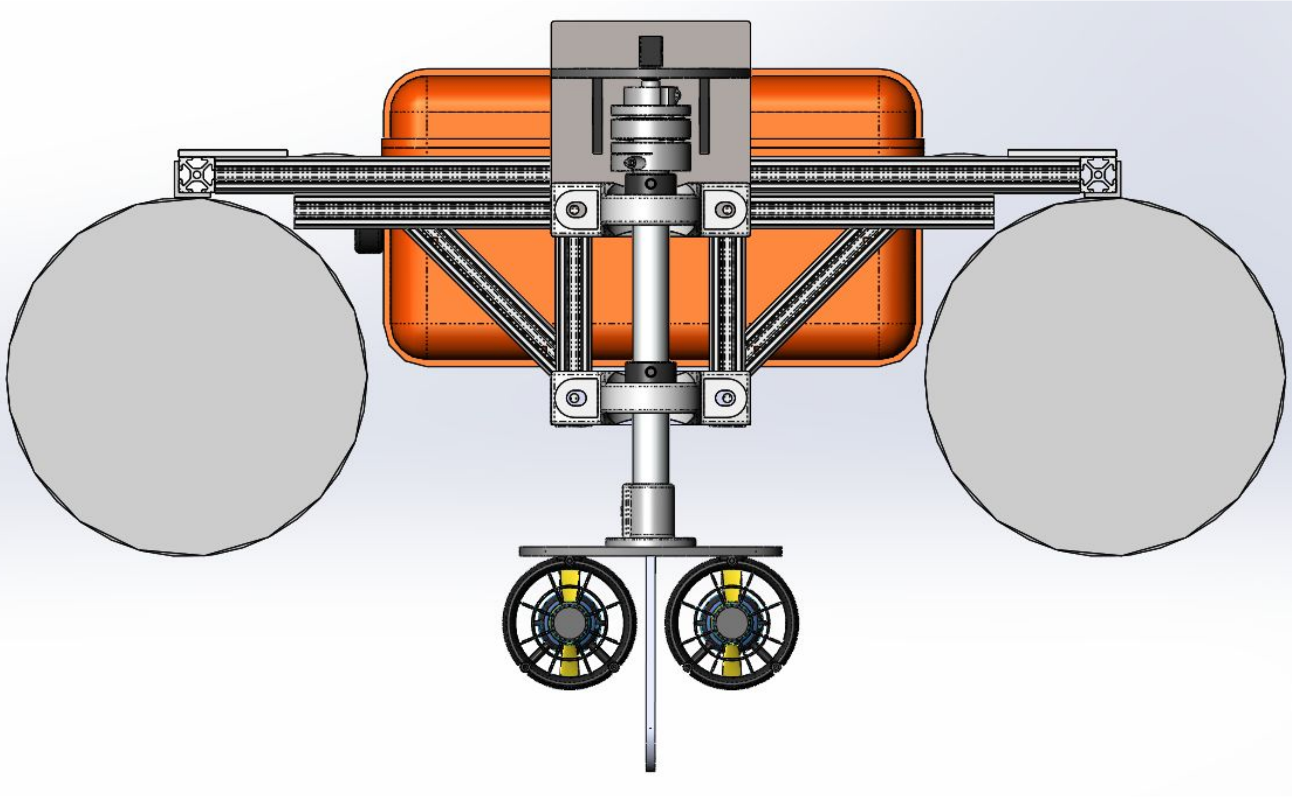
The thrusters that are used on MARV are configured side-by-side and mounted to a steering column as seen in Figures 10 and 11. This configuration lends to the prototype's extremely tight turning circle. This allows MARV to operate in a diverse range of environments where the water surface area may not be large enough for a wide, sweeping turn. Along with the thrusters, the entire steering column (consisting of the thrusters, the shaft and the steering servo) can fold upwards in between the pontoons to protect it during transportation. The folding action allows for the user to drag, carry or wheel MARV without any worries of the steering column hitting objects during transport.



(a)

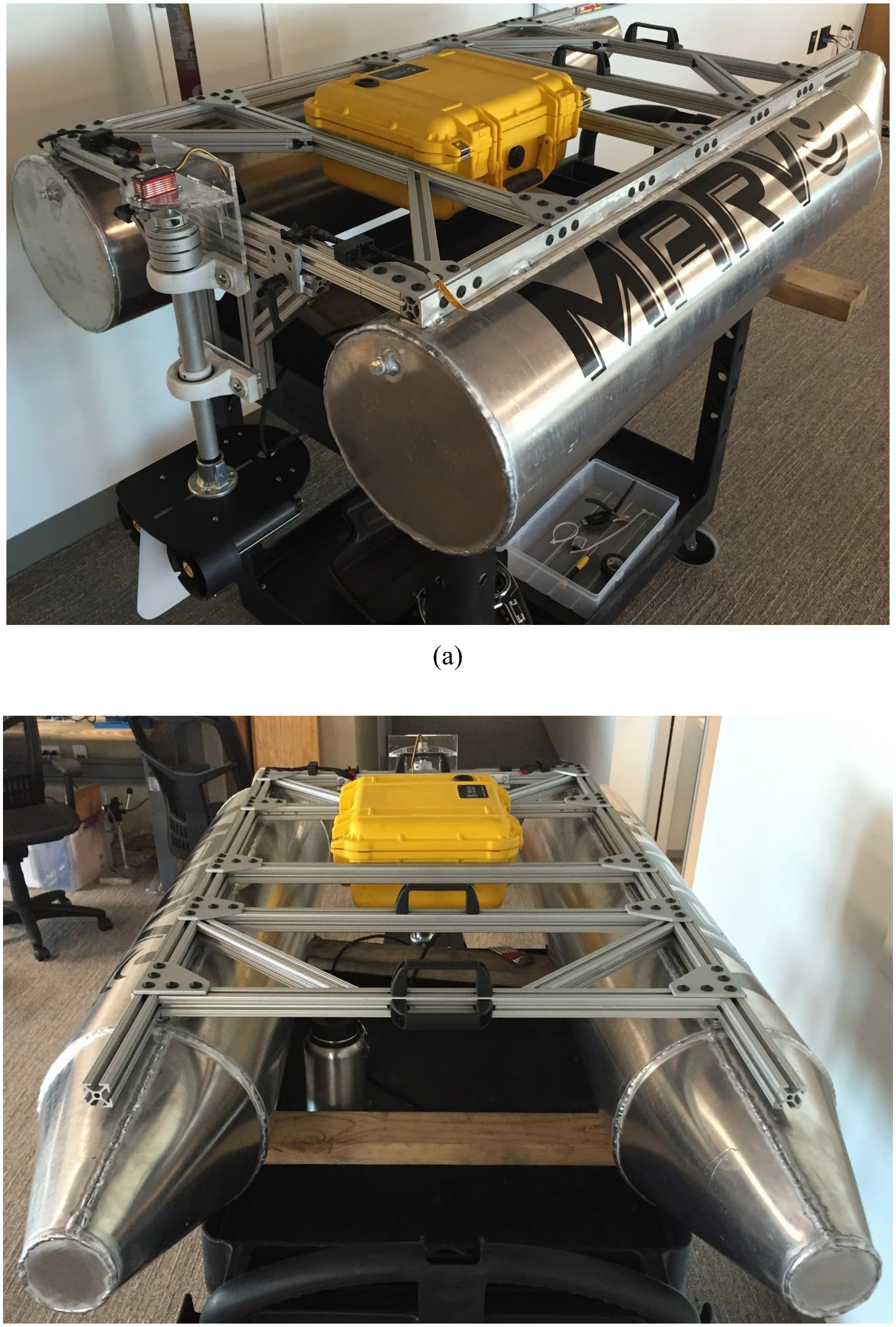


(b)



(c)

Figure 10: Proposed design of MARV hull and structural components where (a) is the isometric, (b) is top, and (c) is the rear views of the proposed design.



(a)

(b)

Figure 11: MARV prototype displaying (a) an isometric view and a (b) front view of the MARV vessel prototype stemming from customer data.

4.3 Analysis of MARV’s Mechanical Design

For the detailed analysis of MARV, the main focus was on the ability to navigate through various fluidic environments and support the desired weight requirement. The method of analysis used is computational fluid dynamics (CFD) to accurately portray the right environmental conditions that MARV experiences in various scenarios. The areas of analysis are as follows:

- Analyze the amount of water MARV can displace and the pressure distribution
- Model MARV in moving fluid to calculate the drag force it experiences
- Analyze deflection behavior of the steering column during operation

It was assumed that the model was satisfactory to support the designed payload. At the max payload, the pontoons will never be submerged lower than half of the total volume. That said, the pontoons have complex nose cone geometry for buoyancy calculations. The assumption was made to consider the nose cone a part of the cylindrical body. This assumption added some error in comparison to the true value but it is assumed to be negligible.

4.3.1 Free Body Diagram

Figure 12 displays the free body force diagram used in the design process and fluids analysis of MARV’s hull. The force distributions were key in determining the max payload that the vessel could support during standard operation. By understanding the active forces on the system, the design was altered accordingly to ensure that the desired performance was achieved.

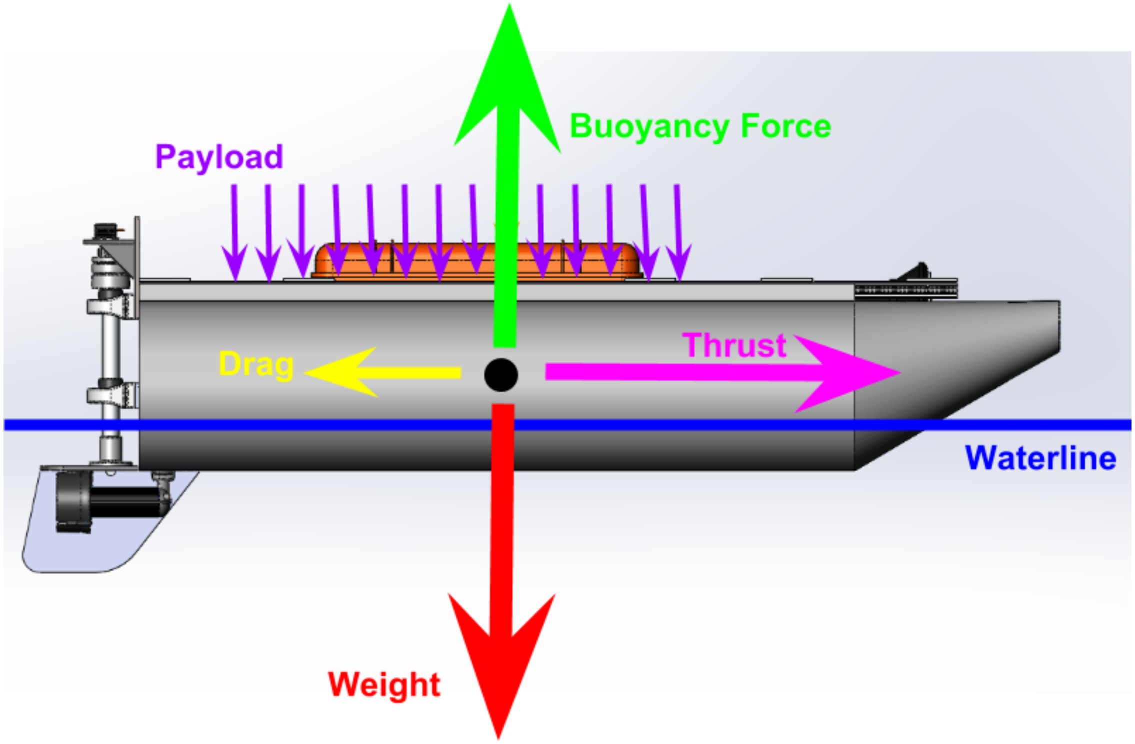


Figure 12: Free body diagram of MARV during expected operation.

4.3.2 Model Used in Analysis

For analysis, a simplified version of MARV was used to truly isolate the pontoons. As seen in Figure 13, the auxiliary components such as the thrusters, steering column and the aluminum framing components from Figure 10 are removed.

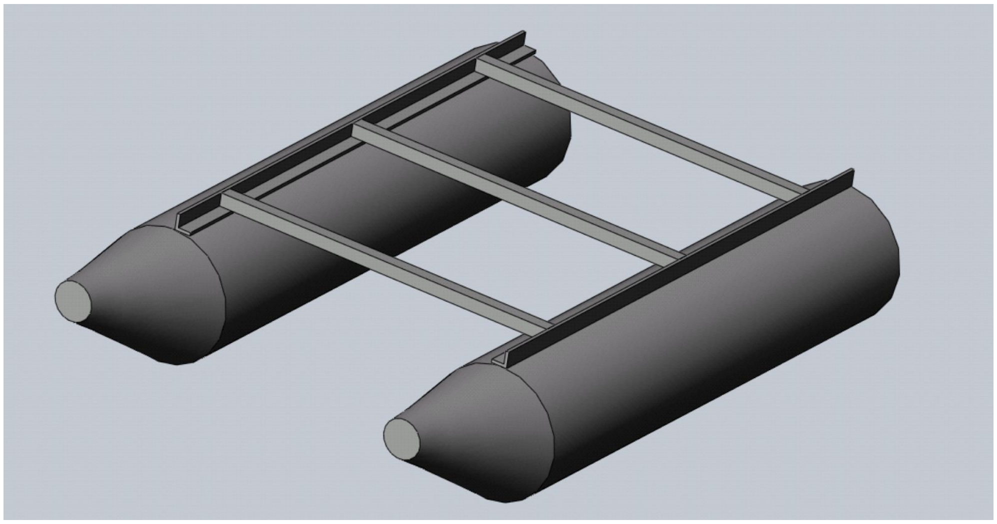


Figure 13: Simplified MARV test model used during simulation.

The two pontoons were connected with three horizontal struts to represent the bridge structure. The material that was used for the analyzed model was the same as the actual components. The pontoons are made of 5052 marine grade aluminum and the steering column is made of 6061 aluminum. The test model simplifications and justifications are listed below:

- 80/20 T-slotted 1" aluminum framing:
  - Replaced with simple 1" square beams in order to simplify the complex cross sectional geometries of the 80/20 material
  - Beams located along pontoons removed due to redundancy
  - Easier to run simulation and mesh the test model
- Steering assembly (shaft, servo, bearings, etc.)
  - Removed from the test model
  - Separate from the focus of the simulation thus they are negligible

The model was tested in a variety of conditions in order to fully analyze the desired elements of MARV during regular operation. In order to characterize potential areas for failure, the model was tested in three areas:

- Max Payload of Both Pontoons
- Total Drag for Both Pontoons
- Steering Column Deflection

4.3.3 Max Payload Analysis

The overarching method of determining the payload of MARV's dual pontoon design is to assume that the amount of water the pontoons are able to displace, the buoyancy force, equates to the amount of weight they can adequately support. There was little concern of the pontoons failing under load due to the construction of the pontoons. The pontoons are manufactured of identical material as commercial pontoons and were professionally welded. The only area that is expected to see potential failure were the points of contact between the angle bracket and the 80/20 aluminum structural framing. Unfortunately, due to the simplifications of the model, this could not be simulated in software.

4.3.4 Drag Force Analysis

In order to properly design a propulsion system for MARV, the forces the pontoons experience must be understood. The force experienced must be overcome by an external source for propulsion to occur. This calculation is encompassing the worst case scenario that MARV will never encounter. By conducting analysis on the worst case scenario, the upper bound of failure has been effectively defined. Any design decisions that fall below this upper bound will be sufficient as a result. The assumptions that describe the "worst case" scenario are:

1. The surface area the fluid "sees" is a 10 inch diameter circle. (Nose cone is effectively absent)
2. The velocity of MARV is 1 m/s. This is the max velocity desired during operation.
3. The coefficient of drag is assumed to be 1.2. This value describes the drag resulting from a flat plate perpendicular to fluid flow.

The absolute worst case scenario yields a drag force of 6.88 *lbf* per pontoon. Therefore, the total amount of force that both pontoons will experience under these conditions is 13.76 *lbf*. This value is what influenced our decision in purchasing our thrusters. We purchased two Seabotix BTD150 thrusters that are capable of 7 *lbf* of thrust each, yielding a total of 14 *lbf* of thrust. This thruster configuration is capable of providing sufficient thrust to a scenario MARV should never encounter.

4.3.5 Drag Force CFD:

Computational Fluid Dynamics analysis was conducted on the actual pontoon geometry as opposed to the worst case scenario hand calculations. Drag forces on the order of 2-4 times smaller was expected. The drag force calculated by the CFD simulation was 2.52 *lbf*. This is a force 3.5 times smaller than the worst case hand calculation, exactly what was expected. See Figure 14 for the pontoon analysis results.

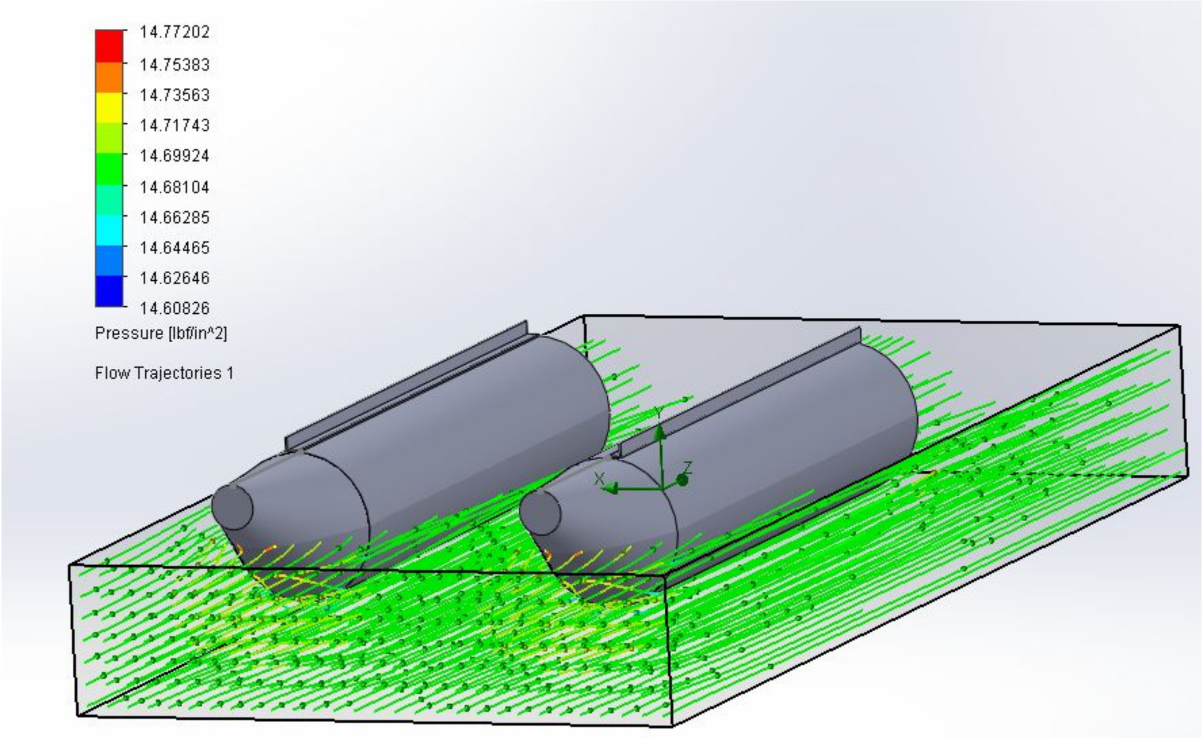


Figure 14: Screenshot of CFD Analysis of Pressure Distribution along the lengths of each pontoon from the isometric view.

4.3.6 Steering Column Deflection Analysis

In order to determine a steering column, the materials and dimensions must be identified. The material's mechanical properties and physical dimensions are listed in Appendix 7. The mode of failure of this particular column would be stress failure due to bending. However, this failure is extremely unlikely to happen unless the steering column would experience an extremely large impact during operation. This incident is extremely unlikely given the speed at which MARV moves through the water. The analysis of operational forces the column experiences is assumed to be the worst possible case again. The assumptions of this analysis are as follows:

- Analyzed as a pipe in terms of mechanical properties
- Experiences a uniformly distributed load
- Treated as a cantilevered beam for deflection analysis
- Area used for Drag Force is the rectangular projection of a cylinder
- The velocity of MARV is 1 m/s. This is the max velocity desired during operation.

After performing the in depth analysis of the pontoon test model, it can be easily seen that MARV can adequately perform the target objectives given the design parameters. The analysis of the max pontoon payload, the total pontoon drag and the max steering column deflection showed that the each of the major areas of failure will not have an effect on MARV as long as the system stays within the specified performance range. The preliminary calculations for of maximum payload at ⅓ and ½ submergence yielded 69.2 lbs and 121.4 lbs, respectively. The preliminary hand calculations and CFD analysis of the drag force yielded 13.76lbf and 5.04lbf respectively. The hand calculations encompassed a worst possible scenario resulting in a high drag force. The design team chose components to be able to operate in these worst case scenarios.

The CFD analysis produced results that heightened our confidence in our design since our factor of safety of 2 was met. The beam deflection analysis also considered a worst case scenario yielding a result that was well within our desired goal of ⅛ of an inch. The maximum deflection calculated with our chosen steering column was 0.008 inches. Continued analysis of other important components, such as the 80/20 cross beams and its corresponding connections/attachments, must be analyzed to ensure that other possible areas of failure are mitigated. Ultimately, the CFD analysis of the test model has proven that MARV will be able to operate as expected based on the design team's performance requirements.

4.3.7 Final Hull Configuration Design

The team analyzed how to implement a version of the stable pontoon construction to maintain low weight, durability, and collapsibility. The designed hull also needed to ensure that the auxiliary attachments (sensors, mounts, etc.) would be supported adequately during operation. This meant that key features such as bathymetric mapping, modular sensor packages, and the navigation/control systems needed to be properly integrated into the hull design while functioning with high accuracy.

Analysis of these design criteria made it apparent that the best configuration for the hull would be to revise standard dual-pontoon implementations that emphasize customization and transportability. These revised pontoons allowed for MARV to be easily transported to different locations as well as broken down and configured depending on the end user.

4.4 80/20 Aluminium Structural Framing

The first subsystem created was the chassis. As seen in the Figure 13 above, the chassis is central to the success of MARV. The chassis design consists of a bridge constructed out of 80/20 aluminum framing that spans across the pontoons as seen in Figure 10 and 11. The pontoons are made of 5052 Aluminum sheeting formed and welded into the pontoon shape via Tungsten Inert Gas (TIG) welding. This is the same method and material used for commercial pontoon boats. The bridge is responsible for housing the power modules (batteries, converters, etc.), onboard computers and the sensors for the system. 80/20 was chosen for the construction of the bridge due to its high configurability and its availability for purchase. 80/20 is an industry standard for various applications making it very abundant in the market place. All of the electronics will be housed inside of a watertight case (Pelican 1550 Case) to ensure the safety and health of the electronics. It is of the utmost importance that the chassis never fails during operation since that would be considered a catastrophic failure. Standard 80/20 struts and attachments that are on the market can be seen in Figure 15.

Figure 15: 1” Extruded 80-20 Aluminum Framing [14]

4.5 Steering Column

The steering column was one of the components that took the most development. The steering column is shown in Figure 10c. The function of this assembly is to provide thrust and steering to the vessel in a compact manner such that MARV will remain transportable.

A major decision that was made early on in the design process was the thruster configuration. A differential drive setup is the Robotic Systems Laboratory standard and was initially the optimal design. Due to the limitations of the Autopilot software package, Mission Planner, we could not configure the thrusters as differential drive. From this, the steering column became a single rotating shaft with thrusters attached at one end, and a servo at the other end.

To address the issue of compactness, the steering column was designed to collapse up into the bridge at the end of each use. In order to secure the shaft in its operational mode, two sliding braces were attached to the bridge to hold the steering column in place while the vessel is functioning. When MARV has completed the mission, the steering column folds up using two hinges and is held in place with a velcro strap.

With the servo attached to a custom brace plate - which is then attached to the steering column - it can rotate the steering shaft. The steering shaft is held in place with two, ultra-corrosion resistant waterproof acetal bearings. Two of these components were used with a 6” distance between them to reduce any bending of the shaft. The shaft is secured to the thruster plate at the other end by a flange.

The thruster plate at the bottom of the rotating shaft is dimensioned to hold each thruster with 3 bolts. In between the two thrusters there is a keel. This keel was introduced to reduce scrubbing of the thruster housing when MARV returned to land, and also to allow MARV to turn when the thrusters are not activated. Without the keel MARV continues to drift forward rather than drift in a desired direction.

5.0 Electrical Subsystem Breakdown

5.1 Power

The next notable subsystem is power – which includes the battery, wiring, wiring connectors, and DC power distribution components necessary to power all of MARV's electronics. Our system can be powered with a battery of any chemistry (lithium-ion, lithium polymer, lead acid, etc.) and can handle voltages between 12V and 24V. All of the electrical components used are displayed in Table 7.

Table 7: Breakdown of secondary components for operation and communication.

Component	Features
Anderson Powerpole Wire Connectors 	Anderson Powerpole wire connectors provide secure, permanently bonded connection points for MARV's wiring. They make things easily ready to plug and unplug for transportation or reconfiguration purposes. These connectors are used often for robotics projects and can be easily obtained and installed. [15]
Castle DC-to-DC Buck Converter or Battery Eliminator Circuit (BEC) 	Castle's Battery Eliminator Circuits (BEC) or DC-to-DC buck converters are small devices that eliminate the need for a receiver and servo battery pack. They draw higher voltage from the motor batteries and drop it to a voltage level that is suitable for your receiver and servos. This is required in applications which draw high power for multiple servos or use more than 3S motor packs. [16]
Powerwerx 75A Position Distribution Block 	The Powerwerx DP-75 distributes power to four positions using compatible Powerpole connectors. The battery gets plugged into the large Powerpole connectors and each position is a parallel connection from the battery. It provides us with a clean and compact way to distribute power that is easily compatible and configurable with our Powerpole connectors. [15]
Powerwerx DC Inline Watt Meter/Power Analyzer 	Powerwerx power monitoring module fits inline with our battery and provides us with real time measurement information of: Amps, Volts, Watts, Amp-hours, Watt-hours, Peak Amps, Minimum Volts (Sag), Peak Watts. [15]

Power is managed appropriately with DC-to-DC converters to ensure that every component, including thrusters and onboard computers, is supplied with the appropriate voltage. All electrical connections use Powerpole connectors on all of the wiring. These connectors make disconnecting and reconnecting, while transporting or reconfiguring, effortless, while ensuring the connections are strong when connected. The connections must also be water resistant in order to negate possibilities of unwanted shorts.

5.1.1 Power Block Diagram

The power system block diagram, in Figure 16, represents the electrical connections between all of MARV's electronic components. The battery is the main source of power for the entire system. A fuse is introduced into the system to ensure the health and safety of all on-board electronics. The power distribution board is necessary to provide power to multiple components at once from a single source. The two BECs (Battery Eliminator Circuit) are utilized in the system to provide a constant voltage output, regardless of input, to the components that are connected to them. The motor driver is a component between the thrusters and the power distribution board to enable the user to manipulate and control the thrusters via software interface.

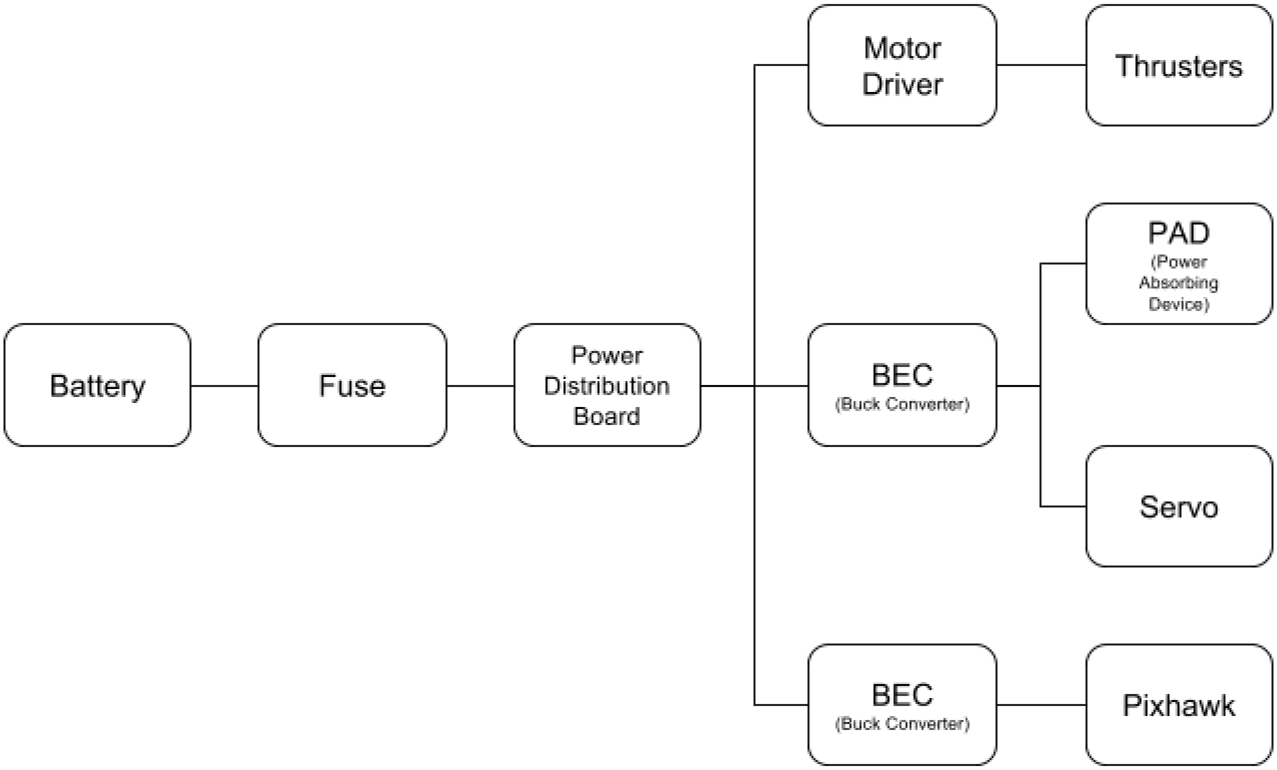


Figure 16: Block diagram displaying the crucial powering components.

5.1.2 Battery

A power distribution block is used in order to power each of the components safely and effectively. The system is equipped with two simple, off-the-shelf DC-to-DC buck converters that step down the battery voltage (between 12-25V) to the Pixhawk at a regulated 5V and to the servo at a regulated 5V. The thrusters are capable of accepting a max voltage from range 12-24V. The thrusters are powered through the DC motor driver component. MARV was tested using a small capacity, 10,000 mAh, Li-Po battery. The battery is displayed in Figure 17 below.

Figure 17: 4S, 14.8V, 10,000 mAh Li-Po Battery [17]

Larger capacity batteries can dramatically increase cost and weight (depending on the chemistry) while at the same time increasing total mission duration and speed. There are also regulations that exist on which battery types can be transported via air travel. Since high transportability is a key objective for MARV, we've created something that is compatible with a range of possibilities that will ultimately be determined by the end user's specific requirements. For example, a user with a low payload could get away with a cheap, long lasting lead acid battery.

An inline DC power monitoring module is used as part of the system that gives real-time voltage readings, current readings, power consumption, and total energy consumption since the mission start to give the user an idea of how much battery power has been used. Current battery voltage is also sent back to the onshore computer for the operator to monitor. This was important in providing us with real mission power consumption data since power consumption is so heavily dependent on individual mission parameters like cruise speed–and thus, hard to calculate on paper. In order to protect against surges, fuses have been placed in the system as well.

5.2 Navigation

MARV utilizes an off-the-shelf autopilot called a PixHawk to navigate the vessel through predetermined waypoints. Using an external GPS module, integrated compass and accelerometer, the PixHawk can obtain real time data regarding MARV's position, heading and error along a predefined path set by the user via software. All of the data collected by the PixHawk gets relayed to the on shore computer via telemetry modules. In the event of an error in the autopilot, the user will be able to regain control of the vessel by switching to manual override via RC transmitter.

5.2.1 Pixhawk Block Diagram

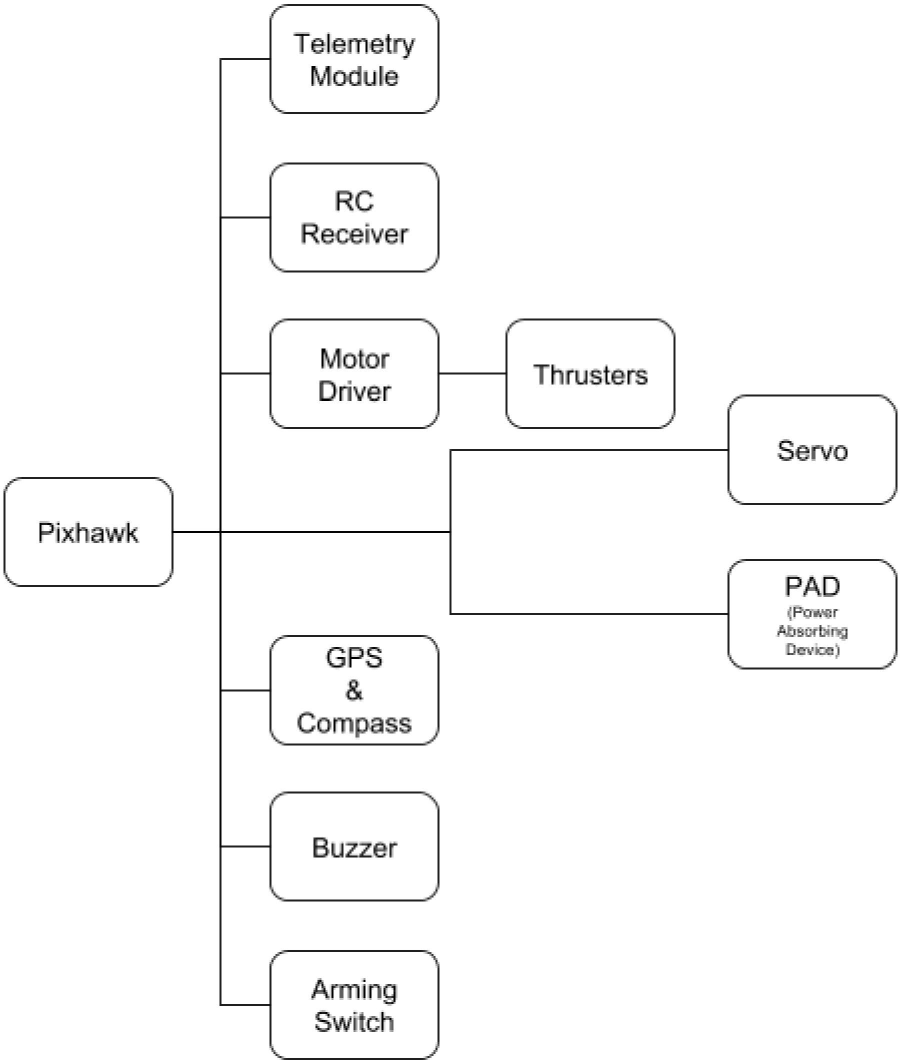


Figure 18: Navigation block diagram displaying key component relationships.

The Pixhawk block diagram illustrates all the components that the Pixhawk interfaces with. The Pixhawk itself has an internal GPS and compass, but it also interfaces with an external GPS and compass to ensure higher accuracy. The buzzer alerts the user audibly through various sequences corresponding to different system configurations. The arming switch allows the user to manually activate the Pixhawk module into operating mode. The RC receiver and telemetry module allow for wireless communication with the user. The RC receiver interfaces with a RC transmitter, also known as a remote controller, to control the outputs of the Pixhawk manually. The telemetry module sends various health data parameters to the onshore computer. The motor driver receives throttle signals from the Pixhawk in the form of a PWM signal, designating the thruster throttle output. Likewise, the Servo motor receives steering signals from the Pixhawk in the form of a PWM signal, designating the position of the servo motor.

5.2.2 Autopilot System: 3DR PixHawk

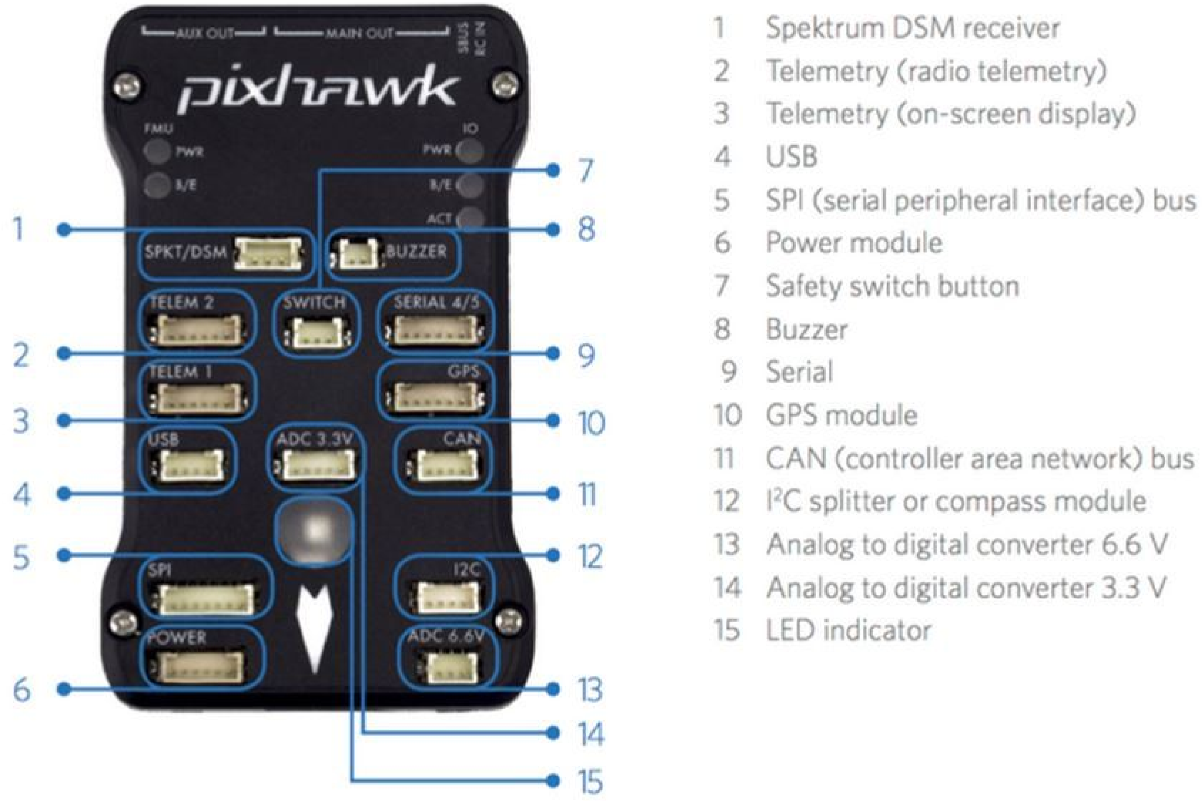


Figure 19: Layout of the 3DR PixHawk autopilot system and the key connections [12].

The 3DR PixHawk autopilot has been chosen as the main mode of navigation during operation. The PixHawk comes with a software package called Mission Planner that allows the user to determine a desired path. This feature provides all of the functionality desired by our team. The benefits of the Pixhawk system include: integrated multithreading, a Unix/Linux-like programming environment, sophisticated scripting of missions and flight behavior, and a custom PX4 driver layer ensuring tight timing across all processes [12]. The PixHawk allows its users to seamlessly integrate this system onto various platforms and lowers the need for new users to spend hours learning complex control algorithms of autonomous vehicles. The lists below describe the key features and technical specifications of the PixHawk.

5.2.3 3DR GPS and Compass Module:

There are three standards of commercial GPS modules: Standard, Professional, and Automotive. The 3DR module falls under the Professional class. The GPS is a U-Blox NEO-7N. The NEO-7N delivers high sensitivity and minimal acquisition times while maintaining a low system power. It is optimized for cost sensitive applications and provides best performance with RF integration. According to the NEO-7 series data sheet, “U-Blox 7 modules use GNSS chips qualified according to AEC-Q100 and are manufactured in ISO/TS 16949 certified sites. Qualification tests are performed as stipulated in the ISO16750 standard: “Road vehicles – Environmental conditions and testing for electrical and electronic equipment”. This particular module has an absolute GPS position accuracy within 2.5 meters CEP.

The compass within the 3DR module is the Honeywell HMC5883L digital compass. (The “taoglas” label on the compass is the distributor) The HMC5883L is a surface-mount, multi-chip module designed for low-field magnetic sensing for applications such as low-cost compassing and magnetometry. This compass can hold a heading accuracy tolerance of 1-2 degrees.

Figure 20: U-Blox GPS NEO-7N (Left) & Honeywell HMC5883L Digital Compass (Right) [22]

5.2.4 Path Determination: Mission Planner Software

In order to determine the path for MARV to follow after reaching the target location, the PixHawk receives input from the user regarding which route to follow. A route for the autopilot to follow can be created using the open source software called Mission Planner (pictured in Figure 22). The software can zoom in on a location using Google Maps satellite images and plot points on the physical picture. The software then has the ability to interpret these points and tag them with GPS coordinates. By picking points along the perimeter of the lake or pond of choice, the software can determine the best orientation and separation distance for the “lawn mowing” pattern. This pattern can also be altered depending on how quickly the mission needs to be accomplished or how thorough the data collection needs to be, as seen in Figure 21.

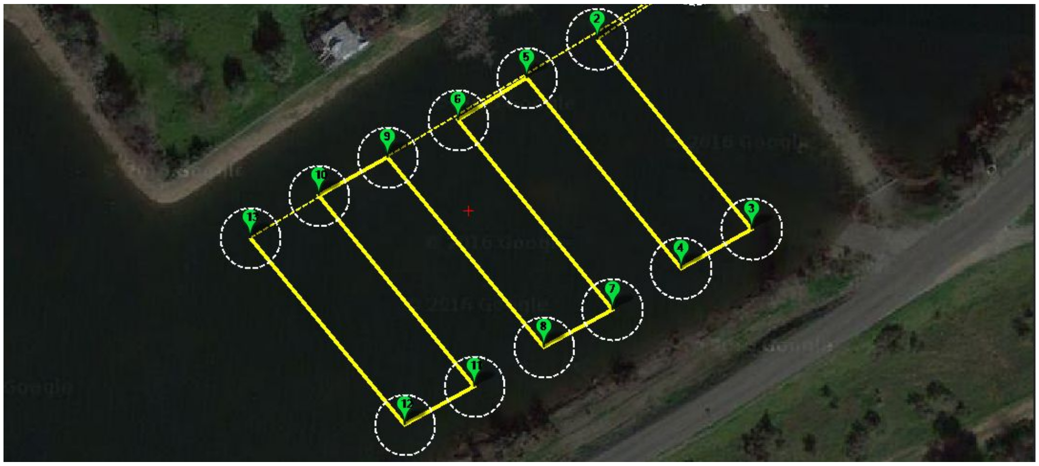


Figure 21: Image of "mowing-the-lawn" path created and uploaded to MARV's autopilot.

Figure 22 shows a screen capture of the live feed of key telemetry information that the system is logging during operation. Ultimately, Mission Planner proves to be the ideal form of navigation control for MARV due to its simplicity and capabilities.

Bat 15.00v 0.2 A 99%EKF Vibe GPS: 3D Fix

Altitude (m) -0.75
GroundSpeed (m/s) 1.04
Dist to WP (m) 34.00
Yaw (deg) 120.19
Vertical Speed (m/s) -0.02
DistToMAV 46.65

hdop: 1.6
Sats: 11 Current Heading Direct to current WP Target Heading GPS Track (Black)

GEO 37.241443 -121.882576 -0.75m
☐ Tuning ☐ Auto Pan Zoom 19.5

Figure 22: Example screenshot of interface of mission from the PixHawk autopilot.

5.3 Movement:

The onboard thrusters are controlled and powered via the Roboteq DC motor driver. This motor driver takes a PWM control signal from the PixHawk autopilot which indicates a desired thrust level. The motor driver then sends the necessary voltage corresponding to this in order to drive the thrusters. The servo motor also takes inputs from the onboard autopilot. With the autopilot sending steering and throttle signals, MARV can be driven completely from the PixHawk. The thrusters are mounted to a plate with a transom and rudder in order to add extra hydrodynamic fluency. This configuration satisfies the driving requirements since it efficiently and effectively meets the performance requirements set forth by the design team.

5.3.1 Thrusters: SeaBotix BTD 150

The SeaBotix BTD 150 thruster is a RSL standard underwater thruster designed specifically for marine robotics. It is a brushed DC motor making it extremely reliable and robust. They are rated at a depth of 150 meters with 2kgf (kilogram force) of forward and reverse thrust at 24 volts.

Figure 23: Image of the SeaBotix BTD 150 [18].

5.3.2 Motor Driver: RoboteQ SDC 2130

RoboteQ's SDC2130 controller is designed to convert commands received from an RC radio, analog joystick, wireless modem, PC or microcomputer into high voltage and high current output for driving one or two DC motors. It is designed for maximal ease-of-use. For space constrained remote controlled applications such as MARV, the controller can directly interface to a dime-size radio receiver. The motor driver can be seen in Figure 24.

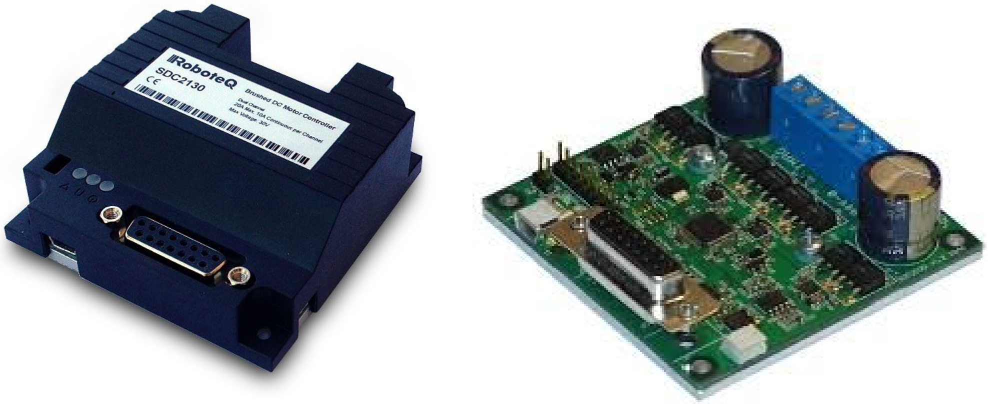


Figure 24: RoboteQ SDC 2130 [19]

5.3.3 Servo Motor: HiTec HSB-9380TH

Instead of making our own servomotor by configuring a DC motor with an additional motor driver, the HSB-9380TH was the optimal off-the-shelf solution. This servomotor interfaces directly with the PixHawk with no additional configurations making it a seamless integration in the MARV system. This model of servo specifically fits the need for MARV’s movement block for the following reasons. It has a sufficient amount of torque, 472 oz-in, for the purposes of moving a steering column to a desired position. It is also a posses a brushless motor with titanium gears for longstanding durability and performance. It also is optimal in terms of a power consumption perspective: low current consumption and constant output power regardless of speed. This specific servo has also won the Reader’s Choice Award for the servo of the year for the 9th consecutive win [20]. The motor driver can be seen in Figure 25.

Figure 25: HiTec HSB-9380TH Servo Motor and PAD (Power Absorbing Device) [20]

5.4 Data Collection:

As previously stated in the introduction, MARV’s main purpose is to provide scientists with a platform capable of autonomous navigation and to accept any arbitrary sensor. To prove that MARV can in fact accept an arbitrary sensor, the team decided to mount a RSL lab standard Garmin Sonar to collect depth measurements. From these depth measurements, a bathymetric map will be generated in post processing. The components necessary to complete this data acquisition are discussed below.

5.4.1 Edison Block Diagram

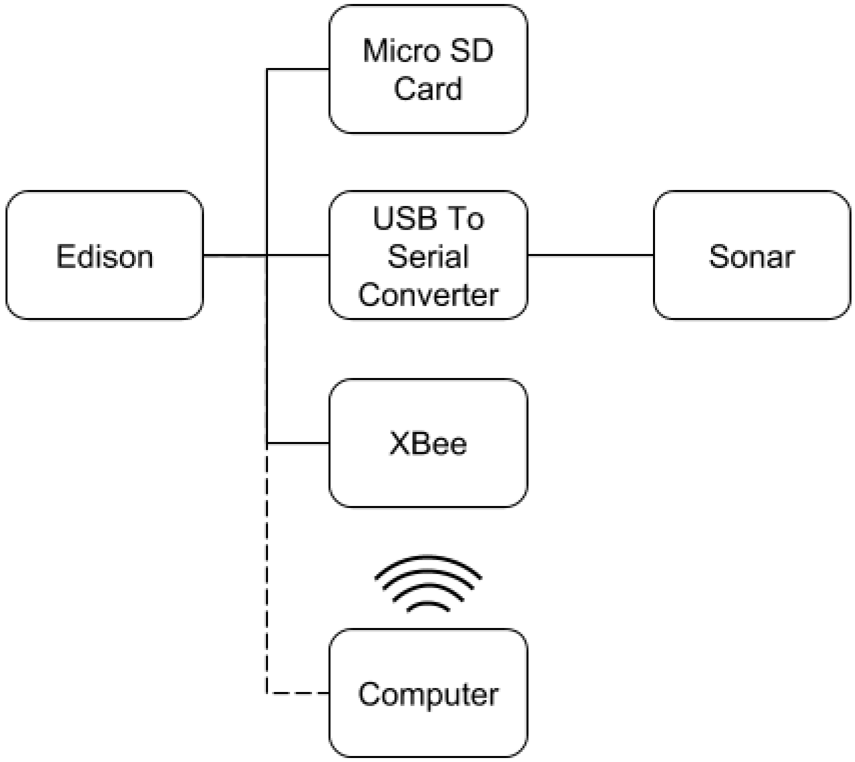


Figure 26: Block diagram of the Intel Edison operation during MARV missions.

The Edison block diagram displays the electrical connections to the components on the Intel® Edison prototyping board. The Edison is connected to two components via serial. The first is the Garmin Sonar; this connection is through a RS-232 USB - to serial converter. The second, is to a radio frequency module: XBee. The Edison also has a port for external storage in the form of an micro SD card. The dotted line and graphic art above the computer block denotes that this connection is wireless. The Edison runs a full Linux OS, therefore, allowing users to connect via SSH.

5.4.2 Onboard Computer - Intel Edison® Prototyping Board:

There exist many different microprocessors that would be able to satisfy the performance requirements of MARV during standard operation. For the scope of this project, the RSL chose to use the Intel® Edison microprocessor platform due to the RSL's partnership with Intel and due to the Edison's versatility and computing power. The Edison's Linux OS (Yokto Project) makes it a very attractive platform to prototype in MATLAB, Python, and Arduino, the RSL programming languages of choice. Powered by the Intel® Atom™ SoC dual-core CPU that includes integrated WiFi, Bluetooth LE, and a 70-pin connector, shield-like "Blocks" can be attached and stacked on top of each other for increased functionality.

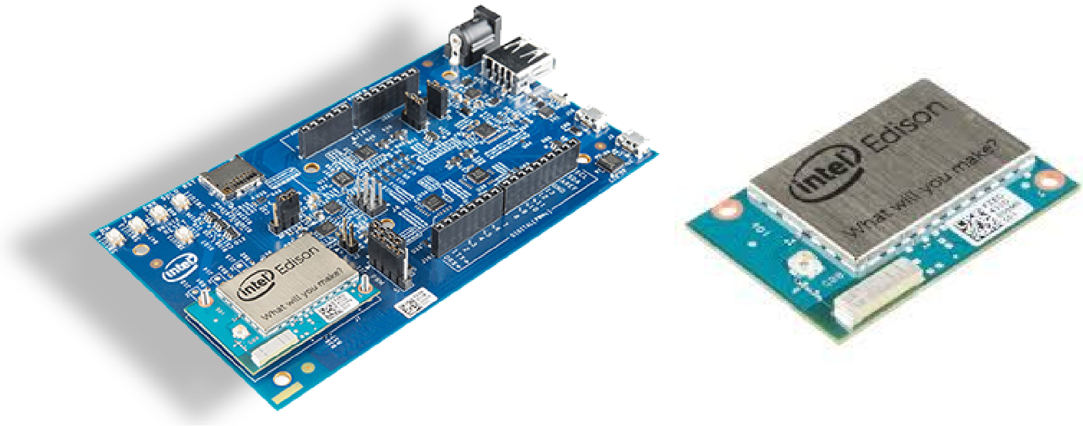


Figure 27: Intel Edison and breakout board that will be used as the onboard computer [13].

The Intel® Edison has a robust set of features packed into its small size. It has many I/O capabilities including, analog, digital, PWM, I2C, and of course Serial. It also includes an Arduino Breakout, which essentially gives the Edison the ability to interface with Arduino shields or any board with the Arduino footprint. This makes its easy to customize by using the many modular attachments that are already used for the open source Arduino boards.

A python script was programmed on the Edison to record serial data from a Garmin sonar. A radio communication is opened between the ground control computer and the Edison to rely commands. The user can tell the Edison when to start logging depth data and when to stop collecting data. When the user requests that the microcontroller cease taking data, the data will be formatted and saved onto an Excel file onboard and exported to an external MicroSD card.

5.4.3 Wireless Communication - XBee Module:

This is the 2.4GHz XBee XBP24-ACI-001 module for RF communication of up to one mile. It has a output power of 60mW. These modules take the 802.15.4 stack and wrap it into a simple to use serial command set. The XBee allows for very reliable and simple communication between microcontrollers, computers, systems, and anything with a serial port. The motor driver can be seen in Figure 28.

Figure 28: XBee Pro 60mW PCB Antenna - (802.15.4) [21]

5.4.4 Data Acquisition - Garmin Sonar:

The decision to use this particular sonar was simple, it is a lab standard. It was ideal for our application because it has a serial interface that integrates seamlessly with the Intel® Edison. It provides NMEA 0183 standard data with the maximum depth of 275 meters. It takes a single pulse depth reading as well as a temperature reading. With a sampling rate of 1 depth reading every 2 seconds, the sonar was easy to integrate into the system and decipher its output. The Garmin Sonar used can be seen in Figure 29.

Figure 29: Garmin Sonar (NMEA 0183) [23]

6.0 Testing Results

In order to verify that all of the components would work together successfully, a series of tests were conducted to ensure that everything was working as expected. The testing procedure ranged from individually testing each component for proper functionality to testing a functioning system on a test body of water. The tests that were conducted were performed as follows: individual testing of components, navigation verification in a controlled arena (i.e. lab parking lot), wet test in a controlled setting (i.e. swimming pool) and field testing on site to fine tune the controller and collect sample data.

Once the system was determined to navigate as expected, sample data was collected to verify MARV's ability to house an arbitrary sensor (in this case, a Garmin sonar) and collect data efficiently. This was conducted by uploading a "mowing-the-lawn" navigation path where data was collected along the way. This data can be seen in upcoming section 5.7.

6.1 Initial Testing - Individual Components:

Prior to any testing of MARV as a system, it was imperative that each individual component was tested to ensure functionality. Each thruster, servo, GPS, compass, accelerometer/ magnetometer, gyroscope, barometer, RF terminal, motor driver, and radio transceiver was tested before assembling the system together.

6.2 Initial Testing - Parking Lot:

The initial testing phase consisted of ensuring that the PixHawk autopilot system would send signals to our components and respond to disturbances. Instead of the PixHawk sending signals to our steering column and thrusters, two servos were receiving the signals.

Figure 30: Initial testing of autopilot accuracy and reliability in a controlled land setting.

A standard servo was receiving the steering inputs while a continuous servo received the throttle input. These "testing servos" would effectively simulate our system interacting with the PixHawk. The changes in the system, aka test servos, would be easily observable. The continuous servo would spin fast or slow indicating the change in throttle and the steering servo would point in the desired heading direction. A mission was uploaded to the PixHawk and both the throttle and steering servos reacted to our external inputs. This component test validated that our components were all powered correctly and were communicating.

6.3 Initial Testing - First Water Test in Swimming Pool:

The first water test was conducted in a swimming pool. This test was to see MARV's pontoon alignment in the water and to manually drive the vessel around the pool via RC transceiver. From this test MARV's turning circle was identified to be much smaller than anticipated at less than one meter.

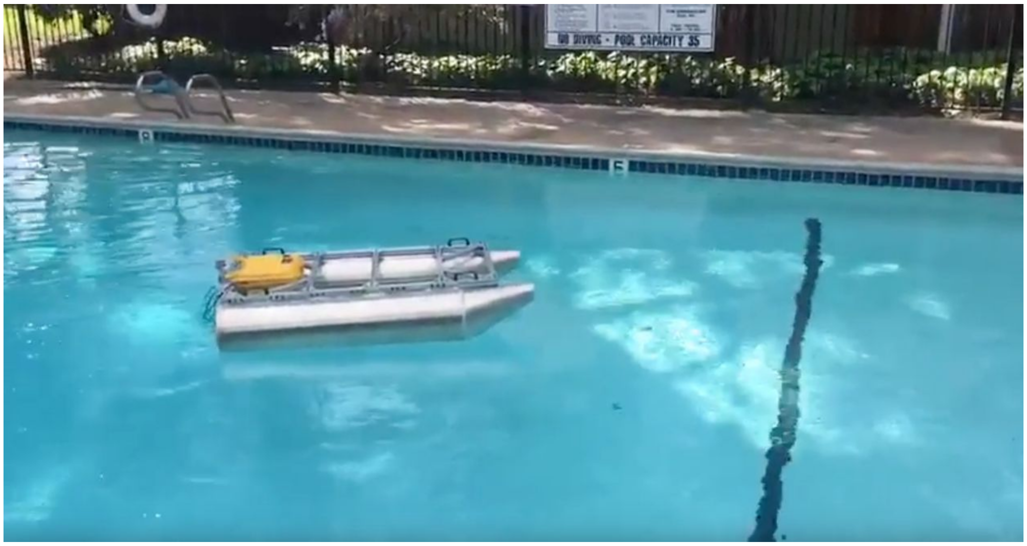


Figure 31: Initial Pool Testing
(This video can be found at: https://youtu.be/MACk9fgKR58)

6.4 Field Testing - Initial Deployments:

The first field deployment was to test if our system was configured correctly to run an autonomous mission. Many functionalities had to perform correctly for this to occur. The mission must be designed correctly, then successfully uploaded onto the PixHawk. The electronic circuits connecting the movement components to the PixHawk must be wired correctly, as well as the connections between the telemetry module and the onshore computer. Finally, all the functionalities from the RC transceiver must perform without failure. These include the three mission modes: Manual control, Return to Launch (RTL), and Auto.

After two days of extensive field testing, all of the functionalities were achieved in rough form. The mission consisted of three waypoints that MARV must reach and then return home to the launch site. The result of this mission is displayed from the Mission Planner software in Figure 32. The yellow path is the designed path and the purple is the actual path of MARV. The path following between points one, two and three have oscillations due to untuned gains, but the RTL command brought MARV directly home. These differences in behavior were attributed to the method of navigation that the autopilot used during its mission. The oscillations stemmed from MARV trying to stay as close as possible to the predetermined yellow path. Since the controller was not tuned correctly, MARV would overshoot the path, which required self correction. The RTL feature used a "connect the dot" method of control where there is no path indicated. This control method simply defines a point of interest and performs a heading lock on said point of interest. Our result was a straight line home due to the mild weather conditions. If the weather was more windy or water currents existed, the path would look more like a semicircle depending on the direction of the disturbance.

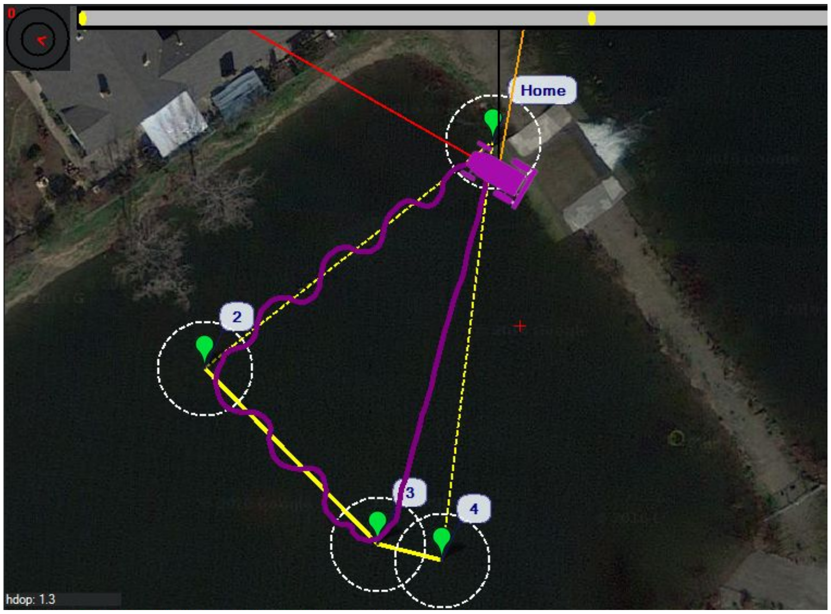


Figure 32: Screenshot of the first MARV mission on water. Depicts the significant overshoot and "weaving" apparent throughout the waypoint navigation.

(A video of this run can be found at: https://www.youtube.com/watch?v=z3SGtLQqhgw)

6.5 Field Testing - Tuning:

After tuning the gains of the control system of the PixHawk, the path following became much more accurate. A more complex mission was then created to further test MARV's ability to follow the route accurately given the newly tuned PID controller gains. As Figure 33 displays, the lengths between each waypoint are much longer than the initial test. This was specifically designed so that MARV would have a longer exposure to potential disturbances to correct. The oscillations shown in Figure 33 along the waypoint legs are far less pronounced than that in Figure 32. This test also verified that acceptable gain values were reached.

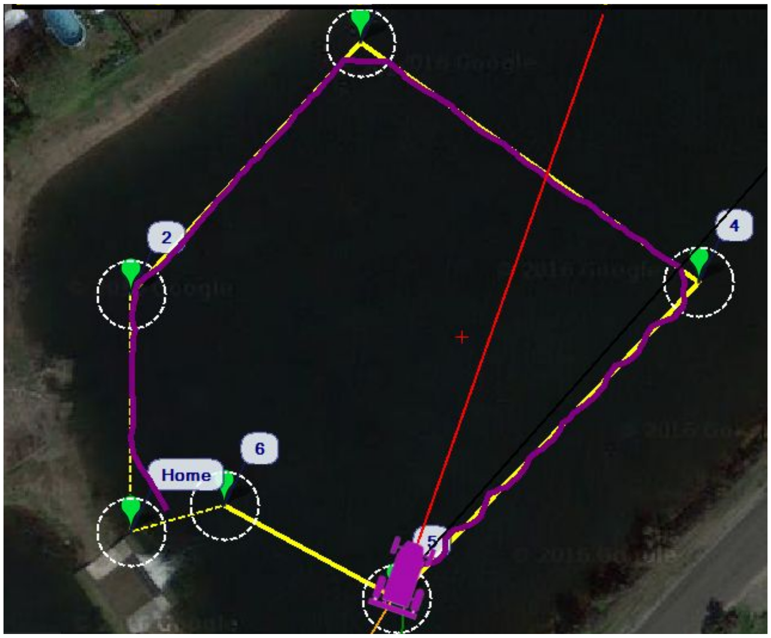


Figure 33: 2nd test with tuned controller. Depicts more accurate navigation throughout mission.

6.6 Field Testing - “Mow the Lawn”:

Once the path following accuracy that was desired has been achieved, the MARV team was confident to program a mission that resembled an actual operation path. This operational path is called “mowing-the-lawn” and can be seen Figure 34.

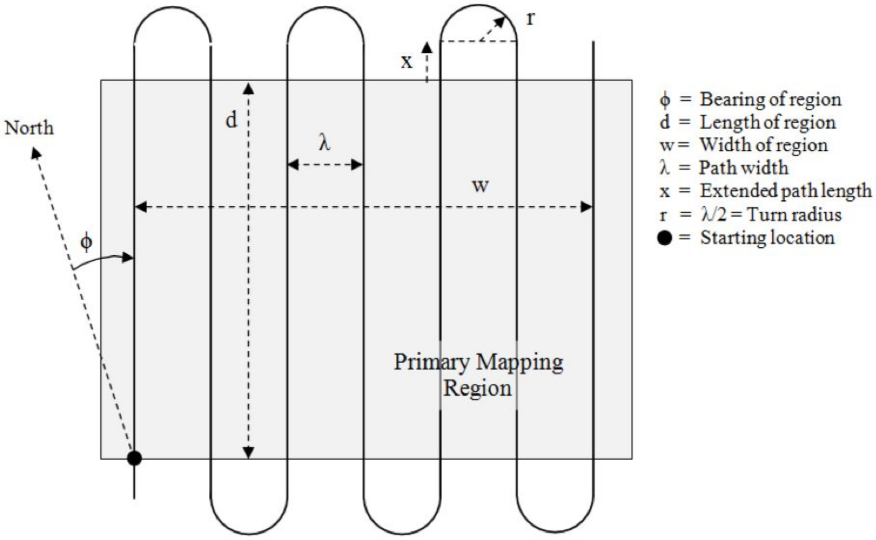


Figure 34: Example “mowing-the-lawn” pattern and parameters used during missions [5].

This path pattern is commonly used in marine research as it covers a large area in the most efficient manner. The “Primary Mapping Region” shaded in grey, in Figure 34, shows where the data is gathered and where the vessel needs to be the most accurate. The path widths, λ, can be determined depending on the desired resolution of the data collection. The orientation of these paths can also be placed in whatever direction desired via the Mission Planner software. The cruise speed and the waypoint radius are also configurable parameters in the software package. The waypoint radius is the radius surrounding the defined waypoint in which the PixHawk will recognize that it has reached its destination.

Figure 35 depicts the successful deployment of the “mowing-the-lawn” pattern. As expected, the performance and accuracy of MARV’s path had minimal deviations. The size of the body of water in Figure 35 is similar to the environment MARV is expected to be deployed in. The water, on average, was five meters deep. MARV is designed to operate in one meter deep waters, therefore, the five meter depth was not an issue for field testing. The total length of the mission was 0.42 km; at an average velocity of 1 m/s the total mission duration was around 8 minutes.

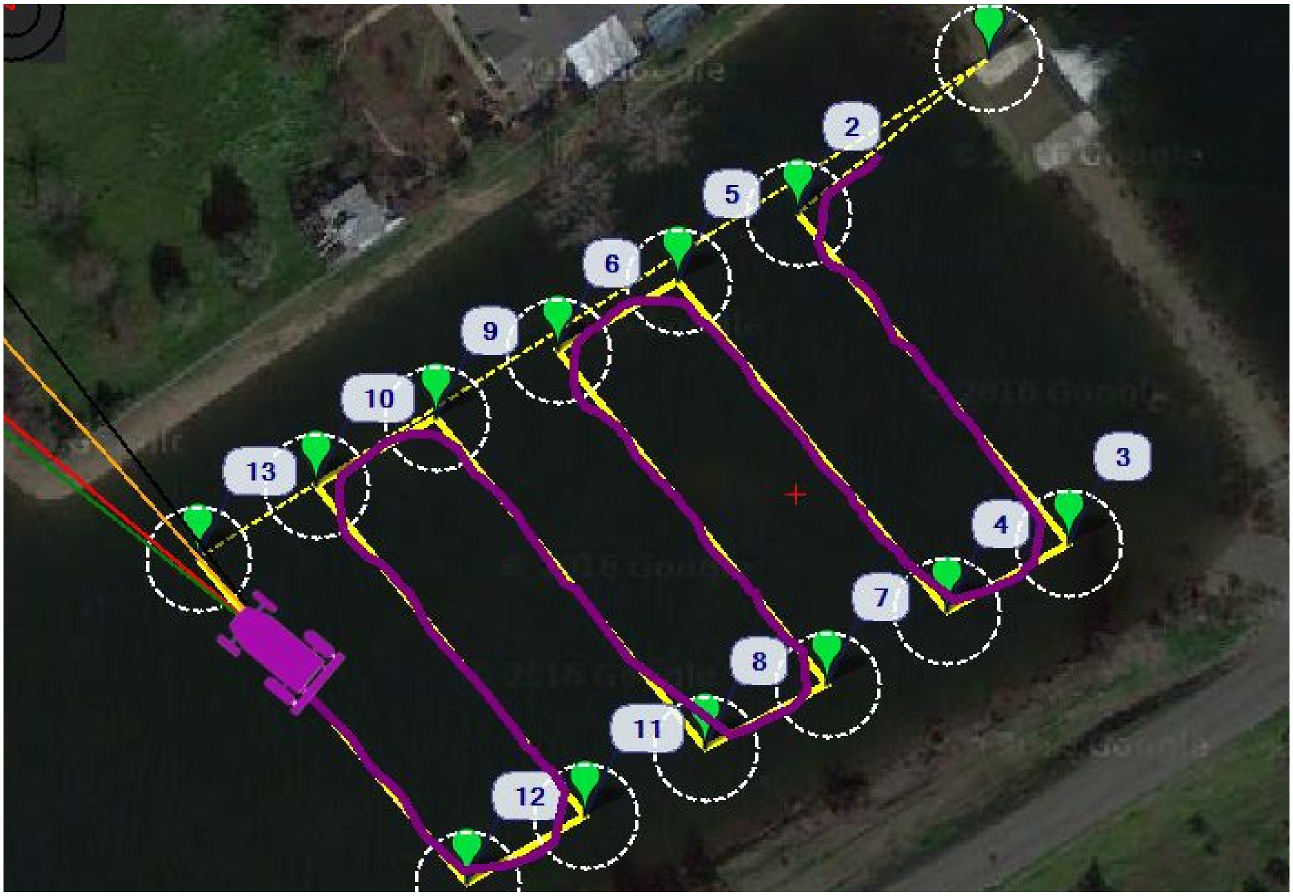


Figure 35: Screenshot of predetermined lawn mowing path and actual route during mission. (A video of this run can be found at https://www.youtube.com/watch?v=oFY5hq9z18o)

6.7 Field Testing - Analysis of Cross Track Error:

The PixHawk comes with a feature where the cross track error is recorded on-board in a Log

File. This error can be plotted in meters versus time, which is displayed in Figure 36 for the mission in Figure 35. The large peaks throughout the graph are when the controller is switching from path to path. For example, in Figure 35 when MARV on it's second to last leg, waypoint 11 to waypoint 12, it must switch to the last leg, waypoint 12 to 13. This switching of paths can be seen in the double peaks around minute 11 in Figure 36. These peaks indicate when the controller has entered the 5 meter waypoint radius, hence the 5 meter error, indicating that a subsequent waypoint must be pursued. Five meters was an empirically defined variable. A waypoint radius of one meter was too tight a tolerance to hold with MARV. The transitions from waypoint to waypoint would experience errors of up to 8 meters. With the 5 meter waypoint radius, MARV actually comes within one meter of the waypoint, which exceeds our project requirements. This 5 meter limit is shown by the dotted red lines in Figure 36.

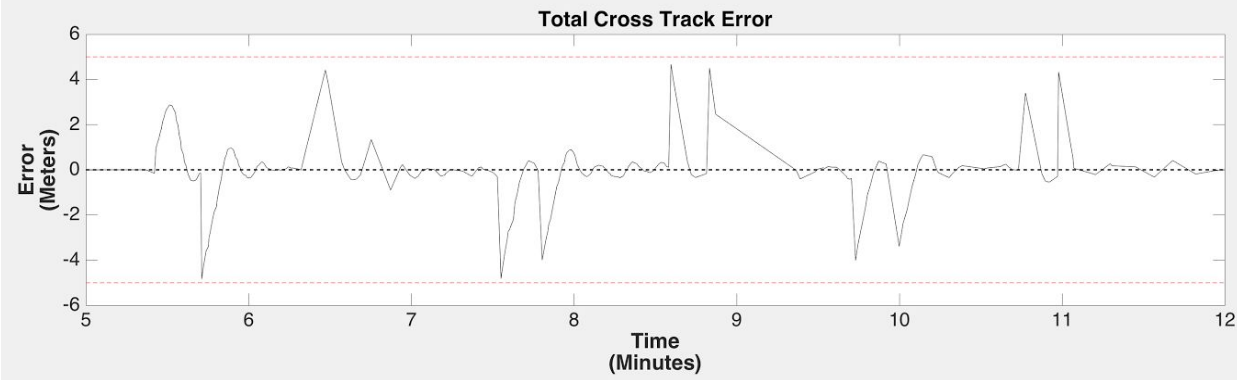


Figure 36: Plot showing cross track error during the
"mowing-the-lawn" mission (Figure 35).

As mentioned, in Figure 34 the shaded region is where the vessel must maintain a high level of accuracy. This is illustrated once again in the blue highlighted lower portion of Figure 37. The blue highlight in the lower portion of the graph corresponds to upper portion of the graph. A new limit parameter is defined to analyze the accuracy of these "straight" paths. In the upper portion of Figure 37, two solid red lines indicate a one meter limit. In the lower portion of Figure 38 displays a granular section of these blue "straight" paths. Our project objective, 3 meter error, is shown by the red dotted line. Our actual error is displayed by the solid red line at one meter. It is clearly indicated that the cross track error for the "straight" paths are well within a one meter tolerance.

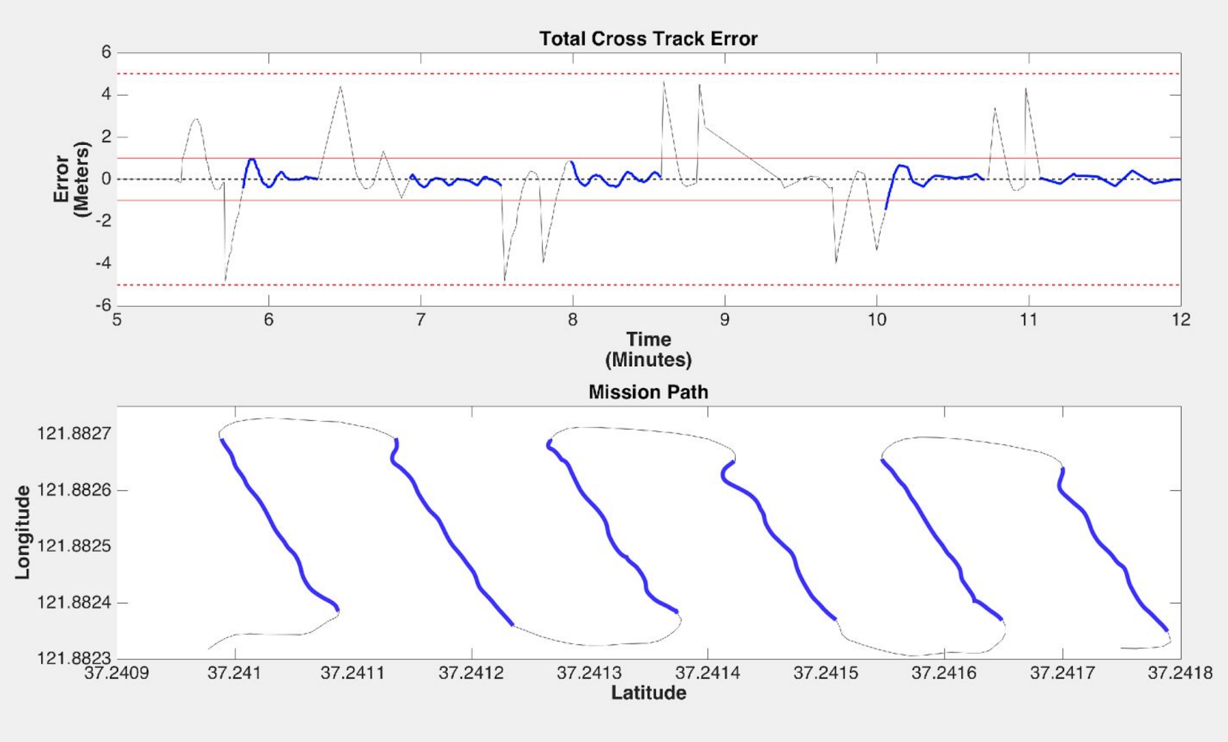


Figure 37: Plot of “mowing-the-lawn” path deviation during mission.

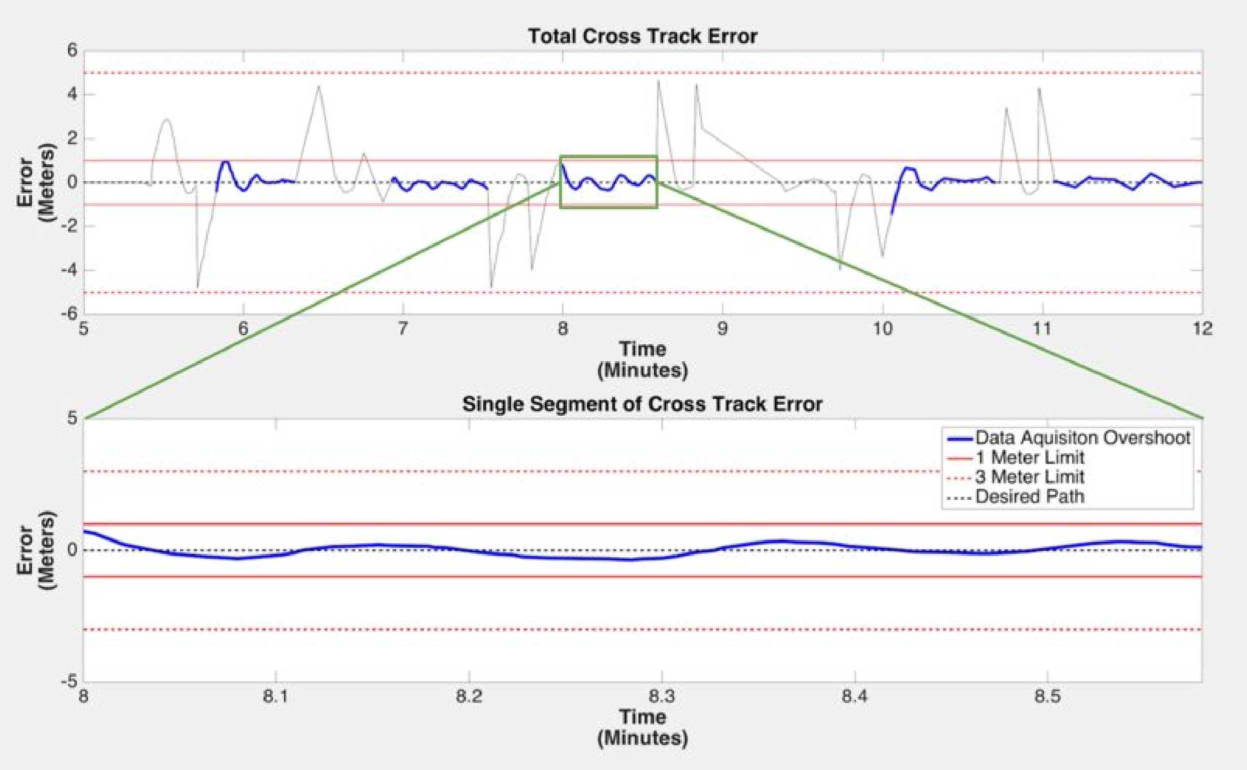


Figure 38 Cross track error of a specific “straight” path.

6.8 Field Testing - Sonar Data Acquisition:

After verifying that the vessel could navigate along a preprogrammed path well within the desired path error, data could be collected to verify how well the vessel could house an arbitrary sensor and have it integrated into the system. It is important to note that MARV serves as a customizable platform for users to install their own instruments depending on the use case. To ensure that MARV could achieve this, and perform data collection successfully, a RSL Lab standard Garmin Sonar was mounted on the 80/20 aluminum chassis to record depth data and generate a bathymetric map of the body of water from that data. Using the same route as Figure 35, depth data was recorded every 2 seconds over the course of the lawn mowing pattern. This data was logged onto the on board Intel Edison and then post processed after the mission's end in MATLAB. The resulting bathymetric map can be seen in Figure 39.

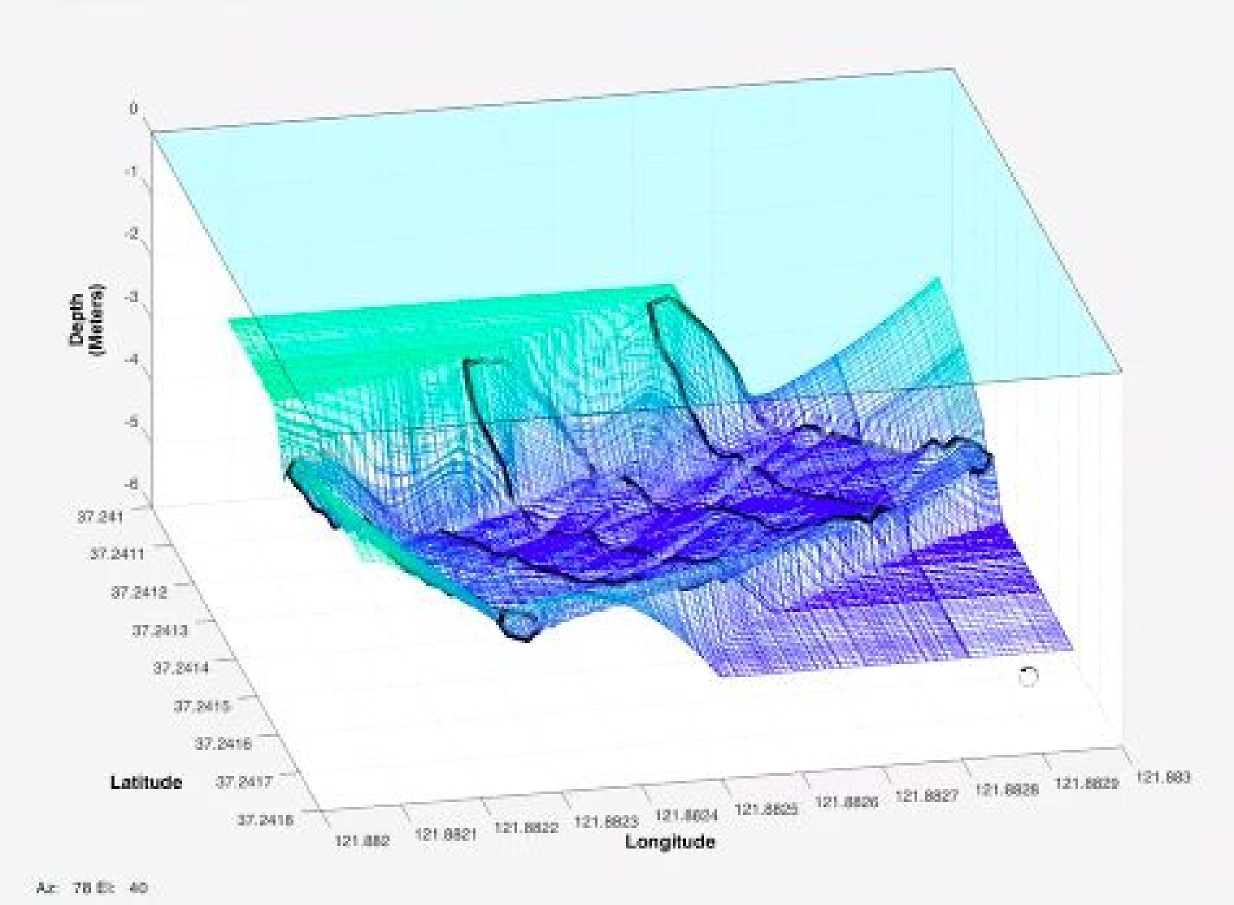


Figure 39: Interpolated bathymetric map generated from depth data during the "mow-the-lawn" path.

As seen in Figure 39 above, the test bathymetric map shows the geographical features located under the water's surface as well as the depth gradient with respect to GPS location (i.e., latitude and longitude). The path can be seen in black showing the lawn mowing pattern used to collect the sonar data over the duration of the mission. As aforementioned, the sonar takes depth measurements at a single points every two seconds along the path rather than collecting constant depth measurements, therefore the need of interpolating the data between the paths arises. This introduces a source of error due to the amount of interpolation making the bathymetric map an approximation of the geographical features. Due to the scope of the project, the team did not design an optimal data acquisition module. The data acquisition was just to prove that an arbitrary sensor can be mounted properly.

6.9 Operational Power Consumption:

Our first data point on the operation was achieved on the run shown in Figure 32. Battery life is the main determining factor for MARV's maximum operation time. For testing purposes, a high-density 14.8V 10,000mAh lithium-polymer battery was used. This provided adequate power and enough range to test for up to an hour on a single charge. After performing multiple tests while collecting data from our Powerwerx power monitoring module, we gained much better insight into MARV's power consumption during operation of a real world mission.

Power consumption is heavily dependent upon how MARV is being operated during a particular mission. Our thrusters are much less efficient the faster they run. Our autopilot software allows the end user to specify a cruise speed. Some users may want to run their mission at a fast speed, while others may want a slow speed to maximize the sample points of the data they collect. For the sake of our testing, we ran missions at 1 meter per second, which is full throttle for MARV. Therefore, the following performance metrics are as poor as they would ever be.

During full throttle operation, ~8.6Amps is being drawn from the battery. From this we can say MARV can operate for an hour (conservatively) with our 10,000mAh battery.

$$\frac{10 Amp \cdot hr}{8.6\ Amp} = 1.15\ hours$$

In terms of distance, MARV can travel roughly 0.4km per amp hour of energy.

$$\frac{1\ meter}{1\ sec} \times \frac{3600\ sec}{1\ hour} \times \frac{1}{8.6\ Amp} \times \frac{1\ km}{1000\ meter} = 0.41 km$$

7.0 Realistic Constraints

Along with technical constraints on the design, there are constraints for MARV out in the real world. These constraints will promote the design of MARV to live up to standards of engineering that satisfy all of the realistic constraints.

7.1 Economic:

The building of MARV is not without economic constraints. Though money is comparatively abundant when compared with other senior design projects, MARV will be used for many years to come by multiple institutions ultimately providing a high return on investment in the long run. MARV was built and tested within a budget which limits the possible capabilities of the vessel. An example of this constraint is shown in testing. Another constraint is the need to produce a vessel that does not exceed the total target cost. Since the vessel is targeted towards users with a wide range of budgets, the total prototype cost must be within realistic values.

7.2 Environmental:

MARV was built to perform its experiments in hostile environments. The environment of operation was a prominent factor when designing the platform. To combat this constraint, we chose to construct the pontoons out of 5052 aluminum, the exact material used for commercial pontoon boats. All of the structural components used for the construction of MARV all exhibited satisfactory performance in harsh environments ultimately showing their versatility.

7.3 Sustainability:

All materials used on the boat must not contain any hazardous chemicals. Because the vehicle operates in isolated bodies of water, we had to ensure that it would not leave any chemical or other contaminants in the water. This fact applied to every component located on the vessel. The motors are DC electric and the batteries will be lithium ion or lead acid, encased within a hard pelican case. Reducing the likelihood of spillage that could contaminate and harm an ecosystem is a must.

7.4 Social:

The data taken from these research missions need to be accurate. The tracking of waypoints executed by MARV must be accurate also. This means that the GPS, navigation and data collection systems must all be working seamlessly together to produce geo-located data that will be useful to scientists. MARV has an obligation to produce such a vehicle or it will sit unused until it is thrown out or dismantled. Team MARV has no desire to see the platform end up that way.

7.5 Ethical:

MARV will be able to serve research institutions, communities and countries alike by collecting priceless hydrologic data. The research results that can be acquired by using MARV will create high quality data from a small scale and highly portable autonomous unit, which would be invaluable to research institutions and organizations all over the world. MARV can be used by research institutions like MBARI, USGS (United States Geological Service) and WHO (World Health Organization) to conduct key research, furthering scientific knowledge and ultimately benefitting society at large. By being able to accurately and effectively characterize water sources, MARV will open up possibilities to expand vital research of our planet's limited resources.

There are a number of ethical concerns pertaining to the MARV project. The main stakeholders that were considered during the course of the project were our team members, the environment, and of course, the end user of our product. Specific concerns are listed in the tables below:

7.5.1 Project Team Ethical Issues

Table 8: Ethical issues regarding the design team.

Ethical Concern:	Key Stakeholder(s):	Our Response:
Prevent copyright infringement	● Design team members ● Original owners of work	● Clearly document where information was gathered from ● Use citations for all work
Safety of team members during design testing	● Design team members	● Follow all design test safety protocols

7.5.2 Ethics In Product Design

Table 9: Ethical issues regarding product design.

Ethical Concern:	Key Stakeholder(s):	Our Response:
Ensure our design is able to accommodate the multiple use cases we have set for it	● End user	● Extensive design research and testing over a wide range of circumstances
Ensure safety of users	● End user	● Ensuring the chassis is unlikely to cut or harm users during proper operation ● Fuses to protect against massive current draws

7.5.3 Social and Environmental Issues

Table 10: Ethical issues regarding social and environmental impacts.

Ethical Concern:	Key Stakeholder(s):	Our Response:
Ensure the health and safety of anyone who might come into contact with MARV	● End user ● Public	● Research and implement safeguards ● Include user warnings ● Integrate emergency shutoff ● Train end user
Ensure that MARV doesn't harm the environment or ecosystems in which it operates any way	● Public ● Earth	● Study potential harmful impacts we could have ● Contain battery in case of leakage
Prevent improper or nefarious usage of MARV	● Public ● Earth	● Make our device only function as intended

Our project teaches us to be ethical in our workplaces as engineers for the sake of our coworkers and organization, as well as for the sake of whomever uses our product and the general public. Our concerns and considerations fall in line with what the Santa Clara School of Engineering expects of us as well as what other organizations such as IEEE outline in their Code of Ethics.

7.6 Reliability:

The likelihood of MARV sinking is low. Both pontoons taking on water to the point where MARV cannot maintain buoyancy is very unlikely to happen. Running out of battery is a possibility. Also, losing control over MARV from the DX8 controller would cause things to fail and MARV would need to be retrieved. The cost of a failure could vary depending upon whether the components get wet. Costs are also introduced to the user who lose valuable time they could otherwise be using to collect data in the field fishing MARV out of the lake.

7.7 Intellectual Property:

Our project is mostly an integration of off the shelf components. All similar products use proprietary navigation systems. The main purpose of MARV is to turn easily accessible (and cheap) components into something that can perform well for scientific collection needs. If we were to bring MARV to market, we would likely need to have contracts with our 3rd party vendors and approval to sell as a part of our system.

8.0 Business Plan

The market for autonomous research vessels is very broad. Many vessels out there can do a variety of things that make it necessary for users to decide how they want to approach their personal goals. This makes the market complex due to the broad range of customer uses that are often not well defined. As a way to counteract this, MARV has the ability to provide a wide range of user functions depending on the use case. Many vessels, ranging from research projects to full production units, on the market today do similar operations targeted towards scientists who wish to complete research on various bodies of water. That said, many of the vessels do not allow for customization or possess a rugged construction required for studies in remote locations. Many vessels are large and bulky, often exceeding weights of 800+ pounds making easy transportability not an option. Other vessels maintain a high degree of transportability but have a high price required to purchase the units, often exceeding $15,000. Based on these competitors out on the market today, there isn't a vessel that bridges the gaps between affordability, high transportability and customization while still achieving a rugged design.

Likewise, the personnel required to use these existing vessels need to have a specific skillset to program and operate them successfully. Many of the vessels on the market today require significant training for users to understand the software and hardware located on the vessel. MARV has embodied easy to use software as well as low level electronics making it easy for new users to learn how to operate the system. A new user who wants to use MARV can learn everything they need to know in roughly 15 minutes. This feature of MARV allows for the customer to spend more time actually collecting the data they are interested in instead of fighting the tool. MARV embodies high transportability and affordability while still maintaining a high degree of customization with a flat learning curve.

8.1 Product Description

Working closely with Santa Clara University's Robotics Systems Lab (RSL), our team has developed an autonomous marine research vessel named MARV. The vessel can be outfitted with a wide range of customer desired sensors and be easily transported to remote locations to conduct critical hydrologic research. Manual override of the system and our autonomous "return home" failsafe has been successfully demonstrated at a distance of one kilometer. The 25 kilogram chassis can collapse for ease of transportation as well as harbor a variety of interchangeable customer desired sensor packages. The software interface requires the same amount of tech savvy as obtaining directions from a Google map, allowing the learning curve for operation to be essentially flat. The final component cost totaled $4,482. Scientists worldwide, from El Salvador to Alaska, have expressed strong interest in such a platform. We have successfully designed, manufactured, and deployed our fully functioning system. MARV is simple, reliable, accurate, transportable, and cost efficient, rendering it an obvious choice for marine scientists to add to their arsenal of data acquisition equipment.

MARV consists of many components that are easy to obtain and operate. The electrical components onboard the vessel are off-the-shelf options that can be purchased with relative ease. Everything from the onboard autopilot, batteries, thrusters, servo and connectors can be bought without having to deal with custom made parts, ultimately reducing costs substantially in the event that a component needs to be replaced. The autopilot system is a repurpose drone autopilot module paired with a personal GPS unit and compass for navigation. Acting as the central hub of the entire system, this hobby class autopilot makes initialization and operation easy for new users as well as purchasing additional components at a hobby store a breeze. This autopilot system provides significant path following accuracy that rivals complex autopilot systems. The onboard autopilot system can also be altered to increase path following accuracy as well as the separation of paths during its "mowing-the-lawn" path pattern.

The mechanical structure of MARV consists of easily obtainable 80/20 aluminum framing and 5052 sheet aluminum that can be purchased from a variety of suppliers around the world. The 80/20 framing has many different components and brackets that fit snugly along the length of the struts, making customization hassle free and easy to install. The two 5052 aluminum pontoons were designed and welded to be as rugged and damage resistant as possible, making them ideal for harsh locations and regions. All of this versatility of the many components allows the end user to save on costs by utilizing low cost parts as well as configuration customization. MARV as a whole is pictured below.

All of MARV's mechanical components allow the mechanical structure to be easily disassembled to increase the level of transportability. The 80/20 aluminum struts and the corresponding attachments can be loosened and removed with an Allen wrench, thus increasing the ease of assembly. The MARV frame can also be configured to accept various instrument and electronics housings such that they are firmly integrated into the system for safe operation. The use of the 80/20 aluminum framing along with the 5052 pontoons makes it very simple for users to customize the platform to fit their individual needs.

8.2 Potential Markets

The market that MARV is targeting consists of scientists and researchers at universities, government institutions and small scientific research firms. These are the same institutions that purchase other similar products and instruments currently out in the market. Many institutions who have purchased or created an autonomous research vessel have one unit that is supposed to have a long use life due to the large investment made on the unit. Often times, the system's investment from purchasing or creating the unit does not get returned. Also, in the event that a unit experiences a failure and needs to be repaired or replaced, it proves to be a very large task because of the large costs and repair time.

MARV will target the users in particular who are studying various characteristics of bodies of water in ways that are labor intensive and not cost effective. Having an option for a low cost vessel that is not limited by capability and transportability will add benefits to these users where other options can not. MARV will be specifically focusing on the lower part of the market where researchers and scientists do not have large budgets to be allocated toward one piece of equipment. The affordability of MARV will also be supported by the high customization level, all but eliminating the need for the purchase of another product to achieve another function. The vessel can be outfitted with any instrument as long as the user has the instrument at their disposal. This quality will add useful benefits to the users on the lower level of the budget spectrum.

Since MARV will not be limited to one use case during operation, the system can be expanded for a wide range of users for different missions depending on the research goal. This makes MARV’s growth in the market far better as compared to other vessels on the market. Along with purchase options, the system could be leased to users who do not wish to own the vessel or only need it for a set amount of time. The introduction of a leasing system does not exist on the market currently. Since many institutions do not have the budget to own expensive research tools, a leasing option would address far more potential customers. This feature will allow MARV to progress in the hydrologic research realm far more quickly than other options.

8.3 Competition

As mentioned earlier, there exists a wide range of other products where their individual functionalities differ depending on the application. Market competition ranges from companies producing multiple vessels as products, to others who have created vessels as research projects where they can be loaned to other users depending on the use case.

In Table 3, it is easy to see that many of the other vessel options on the market today have certain capabilities while lacking in others. For example, the SWATH and SCOAP vessels can complete a wide range of actions but are severely limited due to their extremely large size and weight, making them difficult to transport to remote locations. Others, such as the Z-Boat and Heron, are small scale vessels with high transportability and durability. However, these vessels lack in the key areas of customization and cost, both of which is what MARV is trying to address. MARV is designed to bridge this gap while still maintaining comparable functionality of the much higher priced systems.

8.4 Sales/Marketing Strategies

The sales and marketing strategies necessary for the financial success of MARV as a product depends highly on the sales personnel tasked with displaying MARV’s capabilities to the customer. This is because the market for autonomous research vessels is rather small, making the number of potential customers small as well. As a result, a full display of MARV’s multiple capabilities as well as its high customization features must be shown to the customer. The on-staff MARV salesperson must bring forth what qualities of the vessel bring significant value to the customer. Qualities such as high customization, transportability, light weight, ease of use and so on. Other important features that must be conveyed are the presence of common components and materials making repair and replacement concerns significantly reduced. The purchasing and leasing options must also be disclosed as a way to show customers how affordable it is to use MARV. These qualities of MARV bring significant advantages to the end user as compared to other vessels on the market, so portraying them adequately will be of utmost importance.

8.5 Manufacturing Plan

Since MARV's market is small, there is not a need to house a large inventory of MARV vessels. This is because the amount of buyers of the unit would most likely need only one at any time. Because of this, there would not be a need to manufacture large numbers of the unit, instead they would be built on a made-to-order basis. The main component that MARV would need to have professionally manufactured would be the aluminum pontoons. This is because aluminum welding is a difficult process that assemblers of MARV would be unable to complete adequately. That said, all other components can be bought with relative ease and installed quickly, making the pontoons the only necessary components requiring manufacturing lead time. Once the pontoons have been completed, the system can be assembled and sent to the customer relatively quickly.

8.6 Product Cost and Price

MARV aims to address the needs of scientists and researchers who do not have an unlimited budget to spend on research equipment. Because of this, the system must be affordable to be a viable option for these customers. The target unit cost of the system must be less than $5,000 in order to be highly competitive in the market. Table 2 shows the prices of each component used on MARV to achieve a fully functioning prototype. These components were all purchased at retail value thus increasing the total cost of the unit. In a manufacturing scenario, each component would be purchased at wholesale values in order to develop an inventory of components.

Table 11: Final Detailed Material Costs

Item	Cost	Qty	Total
Seabotix Thrusters	$500	2	$1,000
HiTec Servo	$190	1	$190
80/20 Framing Parts	$712	1	$712
3DR PixHawk	$200	1	$200
Spektrum DX8	$450	1	$450
PowerWerks Elect.	$200	1	$200
RobotEQ Driver	$175	1	$175
5052 Al Pontoons	$350	1	$350

Labor - Welding	$1,000	1	$1,000
3DR Telemetry Radio	$50	1	$50
Pelican Case	$135	1	$135
0.25” Acrylic	$20	1	$20
-			**$4,482**

As mentioned before in Table 11, other competitors that offer similar capabilities as MARV often have a price tag that exceeds $15,000 for a baseline unit. This price point eliminates many of the potential customers that are in the market for an autonomous vessel. MARV’s price point of less than $5,000 provides many of the same capabilities as other companies making it a far better option for a large majority of research institutions.

Other additional costs such as overhead and payroll would be far less than other companies because there isn’t the same need for large buildings and many employees. This is because assembly of MARV can be done by one person over the course of a couple hours and the storage of raw materials is very compact. This would allow the MARV organization to save money while still maintaining low unit costs.

8.7 Services and Warranties

MARV’s main characteristic is that it is rugged and resilient so it can be used in a wide variety of remote locations and minimize the need for repairs and downtime. In the event that the vessel needed to be fixed because of a component failure, a part could be purchased at a nearby store and replaced by the owner quickly rather than sending it back to the manufacturer. The system was designed to be resilient so that there is no need to have a repair service where only the manufacturer can fix the problem. It is our goal that MARV can be repaired by the owner instead of having unwanted downtime.

As mentioned earlier, the MARV platform can be leased and operated by a customer instead of owning the vessel. This would be a potential service that MARV could provide if a customer does not wish to purchase the platform. Depending on the goals of the customer, MARV could be configured by the company instead of the customer, where a service fee would be attached to the purchase or leasing fee. Everything from upgrades in thrusters, battery life or 80/20 configurations could be altered if the customer would rather have it done by the assembler. This service would be another opportunity to accrue revenue from MARV systems instead of purely relying on sales numbers.

Another potential service that the MARV team could provide would be installing a post purchase customer support in case customers have issues when operating the vehicle. This support could take the form of reminding customers of the necessary steps required to arm the vessel or troubleshooting areas of error or malfunctions. The customer support would be a concrete way for customers to be in continuous contact with the MARV team. Another form of contact would be through online tutorial databases for when customers cannot remember steps in the procedure or cannot recall how to operate key functions in the field. This service would take the form of a hotline phone number, online portal, and customer service email account providing customers with several modes of contact with the MARV team.

8.8 Financial Plan

For the financial aspects of the vessel, MARV will be able to provide financial benefits over the course of the vessel's lifetime. Along with the low price as compared to other products, MARV will be able to be configured as well as purchased depending on the customer. If the customer does not want to purchase the vessel, MARV could be leased for a brief time period instead.

An initial investment would be required in order to start collecting components and begin assembly of several MARV's for potential customers. This initial investment would be paid relatively quickly (in a year or less) due to the sale and lease of vessels to many different customers. The investment required for purchasing components versus the sales of several MARV's would create a quick return on investment. Since the initial investment would be paid off quickly, the net present value over the prospective time period would be very close to the initial investment value given standard inflation increases.

Contingency plans would be put in place to mitigate any unforeseen happenstances over the course of MARV's lifetime. This would most likely take the form of a budget cushion as a result. This budget cushion would create wiggle room for MARV in the event that components are back ordered from manufacturers. This extra funding would come from additional investors as well as strategic price planning in order to acquire a small emergency fund surplus. Figure 40 below shows a total business model canvas for MARV and the various revenue streams that can be generated.

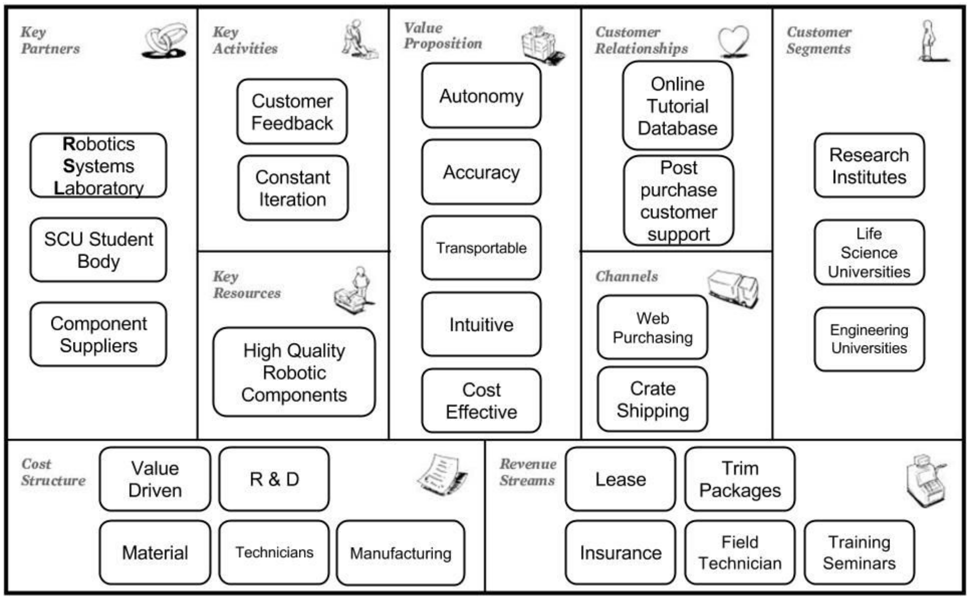


Figure 40: MARV business model canvas.

9.0 Conclusion

9.1 Summary

At the beginning of the project, a series of objectives were defined to establish the scope of the project. These objectives were to create a surface vessel that was autonomous, easy to use, lightweight, transportable, accurate, and cost efficient. We were able to meet and exceed all of these goals.

Through the 10 months of research and development, the MARV team created a viable option for marine researchers seeking an autonomous surface vessel platform. With the utilization of 80/20 structural framing, scientists have a myriad of attachment options available to them in order to mount the sensor of their choice. Due to its high configurability, the 80/20 frame can collapse for ease of transportation. The entire system collapses, enabling MARV to be stored in a standard helicopter side cage for remote transport. At a final weight of 25 kilograms, MARV can be easily carried by two scientist to their desired location. Additionally, the off-the-shelf 3DR autopilot performed exceptionally during field operation. MARV was able to hold a cross track error of less than one meter during the entire duration of its deployments. Mission Planner provides a simple and straightforward to use software interface for the autopilot. Using Google Maps, users can simply draw out the exact path they desire data to be collected from in any body of water in the world. The software then generates the path and uploads it to the autopilot, ready to execute. Finally, MARV provides all of this functionality at a low material cost of $4,500.

9.2 Future Work

Even though MARV has successfully met all of the objectives initially set forth, there are several areas where further iterations could greatly improve MARV's performance. Further development regarding servo performance, servo mounting mechanisms, thruster mounts and pontoon alignment are some of the key components where future work could provide big benefit.

Two areas where future work would increase reliability and performance during operation are mitigation of servo jitter, and structural integrity of the servo mount. The servo chosen for MARV is capable of providing ample torque to rotate the two thrusters. The problem with jitter arose when the thrusters would return to the "middle" position whenever the vessel was going truly forward. The servo could turn the thrusters adequately but the momentum of the two thrusters would cause them to overshoot slightly forcing the servo to correct and bring the thrusters back to middle. This would eventually turn into a never ending cycle causing significant jittering of the servo. This could be fixed by choosing a stronger servo or choosing lighter thrusters. The other area of the servo was the structural integrity of the servo mount. The servo mount was made out of brittle acrylic plastic for sake of rapid prototyping purposes. This material resulted in stressing towards the mounting holes on MARV's bridge. The mount would also bend slightly in a cyclic manner. Future iterations would result in a change of material for more structural integrity.

An additional area for improvement would be redesign of the thruster mounts to mitigate moss collection as much as possible. A problem that was experienced during field testing was that the thrusters would suck in debris that was on the surface of test sites causing MARV to slow down. A redesign of how to minimize this problem would allow MARV to be much more reliable in many different bodies of water where a lack of debris is not always the case.

Finally another area for improvement would be to improve upon the alignment of the pontoons as MARV travels through the water. Similar to when a car is out of alignment, MARV's pontoons were not completely parallel and level–forcing the vessel to stray slightly one direction instead of traveling truly straight. This caused the system to need to correct itself instead of traveling straight. This is a crucial area where efforts could be focused.

9.3 Meeting and Exceeding Intended Specifications

From the testing and analysis that was performed to create MARV, we are proud to have met the desired specifications we originally set out to achieve. Each specification objective along with the actual result is displayed below in Table 12.

Table 12: Required Specifications – Desired and Actual

Specification:	Value:	Actual:
Size and Weight	0.6 x 0.6 x 2.5m 50kg	satisfied 25kg
Path Control	< 3 m	< 1 m
Minimal User Involvement	autonomous navigation	satisfied
Desired Cost	< $5,000	$4,482

With this, MARV will be capable of collecting and delivering valuable hydrologic data for the benefit and advancement of scientific knowledge. This will mean high quality data from a small scale, highly portable and relatively affordable autonomous unit, which would be useful to research institutions and organizations all over the world. MARV can be used by research institutions to conduct key research, furthering scientific knowledge, and ultimately benefitting society at large. By being able to accurately and effectively characterize water sources, MARV will expand vital research of our planet's limited resources.

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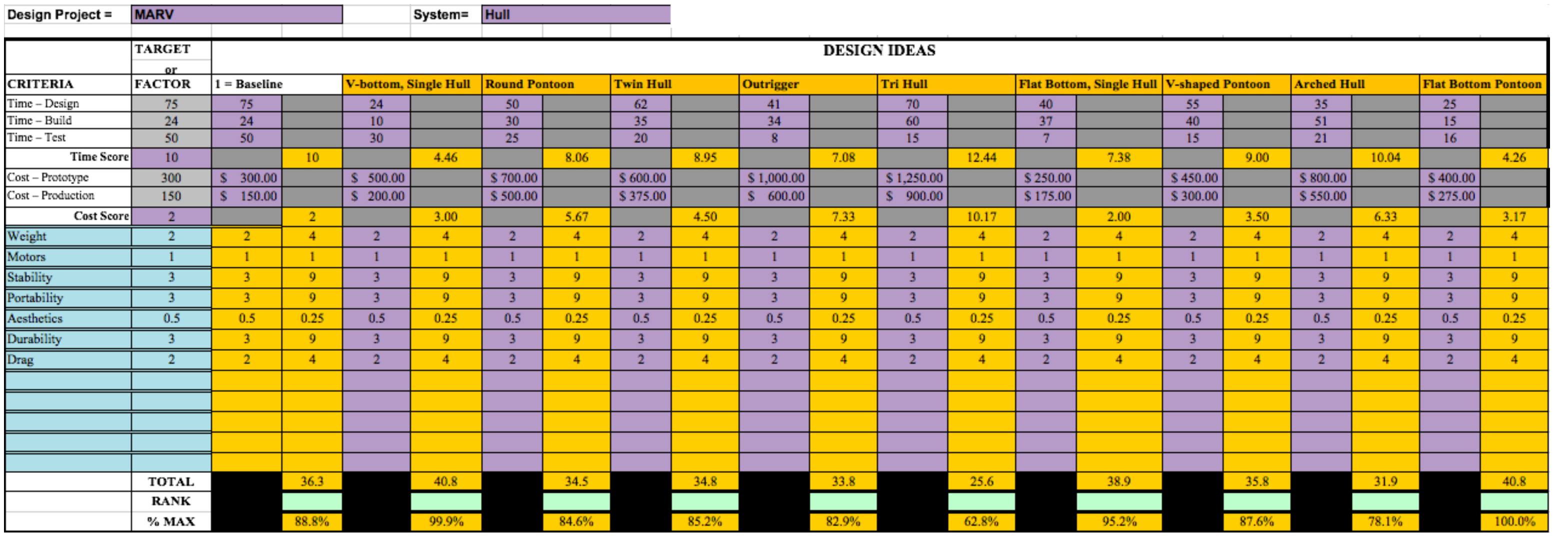
Appendix:

Appendix 1:



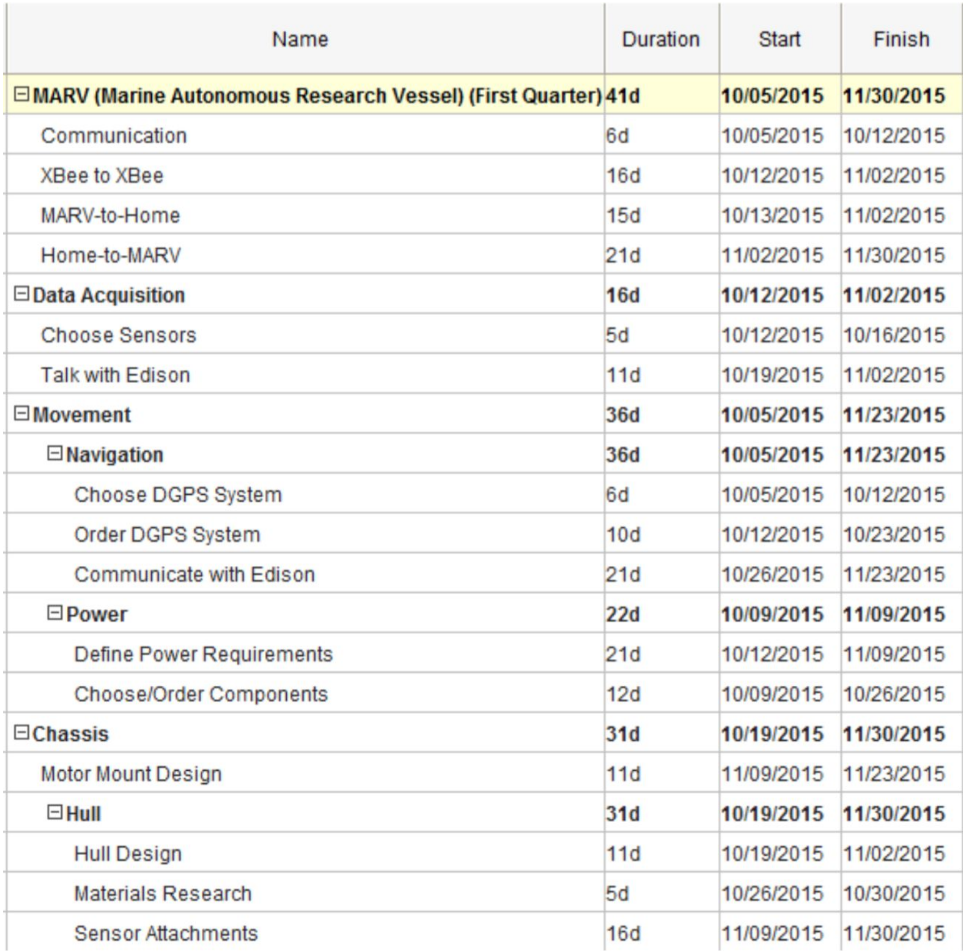
Design Project = MARV System= Hull

	TARGET or FACTOR	DESIGN IDEAS																			
CRITERIA		1 = Baseline		V-bottom, Single Hull		Round Pontoon		Twin Hull		Outrigger		Tri Hull		Flat Bottom, Single Hull		V-shaped Pontoon		Arched Hull		Flat Bottom Pontoon	
Time – Design	75	75		24		50		62		41		70		40		55		35		25	
Time – Build	24	24		10		30		35		34		60		37		40		51		15	
Time – Test	50	50		30		25		20		8		15		7		15		21		16	
Time Score	10		10		4.46		8.06		8.95		7.08		12.44		7.38		9.00		10.04		4.26
Cost – Prototype	300	$ 300.00		$ 500.00		$ 700.00		$ 600.00		$ 1,000.00		$ 1,250.00		$ 250.00		$ 450.00		$ 800.00		$ 400.00	
Cost – Production	150	$ 150.00		$ 200.00		$ 500.00		$ 375.00		$ 600.00		$ 900.00		$ 175.00		$ 300.00		$ 550.00		$ 275.00	
Cost Score	2		2		3.00		5.67		4.50		7.33		10.17		2.00		3.50		6.33		3.17
Weight	2	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4
Motors	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Stability	3	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9
Portability	3	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9
Aesthetics	0.5	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.25	0.5	0.25
Durability	3	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9	3	9
Drag	2	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4	2	4
	TOTAL		36.3		40.8		34.5		34.8		33.8		25.6		38.9		35.8		31.9		40.8
	RANK																				
	% MAX		88.8%		99.9%		84.6%		85.2%		82.9%		62.8%		95.2%		87.6%		78.1%		100.0%

Figure 41: MARV Concept Scoring Spreadsheet:

Appendix 2:

Project Timeline:



Name	Duration	Start	Finish
⊟MARV (Marine Autonomous Research Vessel) (First Quarter)	**41d**	**10/05/2015**	**11/30/2015**
Communication	6d	10/05/2015	10/12/2015
XBee to XBee	16d	10/12/2015	11/02/2015
MARV-to-Home	15d	10/13/2015	11/02/2015
Home-to-MARV	21d	11/02/2015	11/30/2015
⊟Data Acquisition	**16d**	**10/12/2015**	**11/02/2015**
Choose Sensors	5d	10/12/2015	10/16/2015
Talk with Edison	11d	10/19/2015	11/02/2015
⊟Movement	**36d**	**10/05/2015**	**11/23/2015**
⊟Navigation	**36d**	**10/05/2015**	**11/23/2015**
Choose DGPS System	6d	10/05/2015	10/12/2015
Order DGPS System	10d	10/12/2015	10/23/2015
Communicate with Edison	21d	10/26/2015	11/23/2015
⊟Power	**22d**	**10/09/2015**	**11/09/2015**
Define Power Requirements	21d	10/12/2015	11/09/2015
Choose/Order Components	12d	10/09/2015	10/26/2015
⊟Chassis	**31d**	**10/19/2015**	**11/30/2015**
Motor Mount Design	11d	11/09/2015	11/23/2015
⊟Hull	**31d**	**10/19/2015**	**11/30/2015**
Hull Design	11d	10/19/2015	11/02/2015
Materials Research	5d	10/26/2015	10/30/2015
Sensor Attachments	16d	11/09/2015	11/30/2015

Figure 42: Detailed timeline for Fall Quarter 2015.

Timeline (Winter Quarter):

● Fully Functional Prototype Complete	1/9/16
○ Testing & Software completed over Christmas break	
● Final Hull Design Complete	1/23/16
● Manufacturing of Hull Complete	2/19/16
● Integration of Sensors and Control Systems	3/11/16

Timeline (Spring Quarter):

● 3 completed field tests	3/29/16
● Completed refinement of PID controller	4/16/16
● MARV Complete	5/13/16
● Thesis Complete	6/3/16

Appendix 3:

Table 13: Prototyping Costs

Prototyping Costs (Mechanical Components)		
Item	Description	Cost
80-20 Extrusion	Structural frame where all components are housed	$85
80-20 Accesories	Mechanical components to attach frame	$215
Military Rucksack Frame	Transportation device	$40
5052 Aluminium Pontoons	Floatation device	$200
Pelican 1450 Case	Housing for electrical components	$100
2 Blue Robotics T200 Thrusters	Propulsion system	$340
High Torque Servo Motor	To rotate the steering column	$200
Servo-Steering Column attachment	Mating the servo to the steering column	$40
Thruster and Servo mounting bracket	Attach thrusters and servos to the frame	$50
TOTAL		$1,270

Appendix 4:

Project Safety Review of MARV:

Manufacture

In manufacturing MARV, there exists some safety concerns. The use of power tools and equipment will be necessary when constructing the hull and frame of the project. This construction will consist of using the equipment in the Santa Clara University Machine Shop as well as the Santa Clara University Maker Lab. As with any construction, proper knowledge and understanding of how to use the equipment will be necessary to remove potential areas for team members to be injured. It will be essential to be trained to use the equipment and follow all safety protocol set forth by Santa Clara University. Being aware of the potential safety risks in operating the power tools will be essential to minimizing safety risks. Having this understanding/training will give the manufacturers (including the design team) the necessary procedures to construct the main components of MARV.

Assembly

In the assembly of MARV, many of the safety concerns that are evident in manufacture can be applied to the assembly as well. The system will require tools and machine shop capabilities to assemble MARV to the design specifications. In that regard, similar courses of action will be required to safely complete assembly with no injury to the design team. There does not exist any other areas that of safety concern during assembly in the opinion of the design team.

The other aspect of assembly that must be noted is MARV's assembly at the site of the user's choosing during normal operation. The system is designed to be easy transportable in order to reach remote research locations. That being said, the system will need to be broken down into separate modular components (modules that are still being designed and discussed), be self contained in one package and then be reassembled once the system in at the target location. This modularity and breakdown is designed to minimize difficulty for the assembly of MARV and which won't be labor intensive. This part of the project provides no apparent safety risks to the user in this facet of the project.

Test/Operation

For testing and operation, there exists several areas of potential safety risks. The thrusters (when out of the water) will be exposed any time the system is not in direct use. It is important to recognize that the propellers of the thrusters can inflict significant injury if the user member comes into contact with them. This makes it important to always disconnect power from the system during assembly and testing of the system. MARV will also use high power which increases the potential of electric shock providing another reason to ensure that the system is disconnected from power when handling the unit. It will be important to ensure that the system is completely powered down before opening the Pelican case containing all of the system's electronics.

The vast majority of potential safety risks that will presented during testing and operation will be during the assembly and initial deployment of the system. During operation, MARV will be traveling autonomously along predetermined routes. This means that there will be virtually no physical contact between the user and the system. Since this will be the case, the design team see no potential safety concerns for the user as well as the team. In the event that MARV stops operating as planned or loses power in the middle of a body of water (especially during testing), it will be necessary to retrieve the system through appropriate means (boat, wade, etc.). This "rescue" will prove to have safety concerns if not done in a thought out and careful manner. It will be necessary for the rescuers to wear appropriately fitted life vests and safety gear whenever it is required for a rescue mission. Operators of the rescue boat must not display reckless driving and obey all maritime laws. It will also be necessary to be knowledgeable of the water conditions and weather before leaving shore and use common sense before embarking on any potentially dangerous activities. This will mitigate any potential for bodily injury for people in contact with MARV.

Display

MARV will utilize a combination of protective coverings and signage to prevent any potentials for safety concerns. The system will use coverings in the areas of the thrusters and main hardware to prevent any injuries of the end users. The hardware and main electrical components will be housed inside of a watertight container to make sure that outside forces will not come into contact with sensitive equipment. This container is used to prevent any short circuiting and electric shock to the user. It will be necessary to completely power down the system before the case can be opened.

The thrusters will use propeller covers to protect the propellers from any contact with objects as well as protect users and the design team from ever touching the prop while it is spinning. Even in the case that the propellers are powered on, the prop covers will still provide protection from any bodily injury. All of these features will be displayed using warning graphics and stickers to remind the users of the potential areas for injury. This will be aimed to reduce and be a constant reminder to the user to be aware of what he/she is doing. By being smart and not acting reckless will be an effective tactic to minimize error and safety concerns.

Storage

The system will be stored in places free from any potential for damage since there are sensitive instruments on board. During travel, MARV will be broken down and transported in a manner that protects the vital components of the system. The system will be designed such that the more durable parts of MARV will be the primary objects that come into contact with the outside world during transport. With that said, various components, like the frame and pontoons, will be made of strong material to protect the system from damage and increase durability. The system will be rather heavy (~110 lbs) and paired with components with very little give, there exists a risk for smashing fingers and toes. This weight will also present possible back injury if not carried appropriately. Any users and team members that are planning on storing MARV will need to be aware of their surroundings and appendages to reduce the risk of inflicting personal injury.

Disposal

At the end of life of the project, the system will need to be broken down and disposed of appropriately. Many of the system’s components will consist of plastic and metal materials. This will make disposing of these components easy as many of them can be recycled to be made into new products and used in different projects. This component of MARV makes the system extremely versatile when it is required to be disposed of. With that in mind, the design team agrees that this aspect of the project is free from any safety concerns for users.

Other areas of the project requires a more in depth process of disposal. The electronics can not be simply thrown out and recycled in the manner that many of the other components are. Things like the batteries and electronics must be disposed of in a safe manner to reduce any risk of coming into contact with dangerous chemicals and materials. The batteries will be need to be disposed of in an environmentally friendly manner. It will be important that the end user consults his/her local battery disposal station to dispose of the batteries properly. The electronics (if not salvageable) must be disposed of in an appropriate area to reduce any chances of safety risks. It will be important that the end user disposes of these components in an appropriate receptacle similar to batteries.

Appendix 5:

Technical Specifications of Onboard Components:

Table 14: 3DR PixHawk Autopilot

Key Features*	Technical Specifications*:
- Advanced 32 bit ARM Cortex® M4 Processor running NuttX RTOS - 14 PWM/servo outputs (8 with failsafe and manual override, 6 auxiliary, high-power compatible) - Abundant connectivity options for additional peripherals (UART, I2C, CAN) - Integrated backup system for in-flight recovery and manual override with dedicated processor and stand-alone power supply - Backup system integrates mixing, providing consistent autopilot and manual override mixing modes - Redundant power supply inputs and automatic failover - External safety button for easy motor activation - Multicolor LED indicator - High-power, multi-tone piezo audio indicator - microSD card for long-time high-rate logging	*Microprocessor:* - 32-bit STM32F427 Cortex M4 core with FPU - 168 MHz/256 KB RAM/2 MB Flash - 32 bit STM32F103 failsafe co-processor *Sensors:* - ST Micro L3GD20 3-axis 16-bit gyroscope - ST Micro LSM303D 3-axis 14-bit accelerometer / magnetometer - Invensense MPU 6000 3-axis accelerometer/gyroscope - MEAS MS5611 barometer *Power System:* - Ideal diode controller with automatic failover - Servo rail high-power (7 V) and high-current ready - All peripheral outputs over-current protected, all inputs ESD protected

**Key features and technical specifications cited from 3DR's PixHawk web page [12]*

Table 15: Intel Edison Microcontroller

Computer Chip*:	Auxiliary Inputs/Outputs*:
- Intel® Atom™ system-on-a-chip (SoC) based on leading-edge 22nm Silvermont microarchitecture including a dual-core CPU and single core microcontroller (MCU)	- Compatible with Arduino Uno (except only 4 PWM instead of 6 PWM). - 20 digital input/output pins including 4 pins as PWM outputs

- Integrated Wi-Fi, Bluetooth LE, memory, and storage - Support for more than 30 industry-standard I/O interfaces via a 70-pin connector - Support for Yocto Linux, Arduino, Python, Node.js, and Wolfram - Open source community software tools enabling ease of adoption and inspiring third-party app developers to build apps for consumers. - EDI1.SPON.AL.S (System-On-Modules - SOM Edison Module IoT Internal Antenna)	- 6 analog inputs - 1 UART (RX/TX) - 1 I2C - 1 ICSP 6-pin header (SPI) - Micro USB device connector OR (via mechanical switch) dedicated standard size USB host Type-A connector - Micro USB device (connected to UART) - SD Card connector - DC power jack (7V – 15V DC input @ 500mA)

Digital pins 0 to 13 (and the adjacent AREF and GND pins), analog inputs 0 to 5, the power header, ICSP header, and the UART port pins (0 and 1) are all in the same locations as on the Arduino Uno R3 [13]. Additionally, the Intel® Edison with its attached Arduino Breakout includes a microSD card connector, a micro USB device port connected to UART2, and a combination micro USB device connector and dedicated standard size USB 2.0 host Type-A connector (selectable via a mechanical microswitch) [13].

**Key features and technical specifications cited from the Intel Edison web page [13]*

Table 16: SeaBotix BTD150 Thrusters

Performance	
Maximum Forward Thrust @ 16V	2.4 lbf
Maximum Reverse Thrust @ 16V	3.0 lbf
Maximum Forward Thrust @ 12V	1.7 lbf
Maximum Reverse Thrust @ 12V	1.8 lbf
Electrical	
Operating Voltage	6-28 volts
Max Current	6 Amps

Max Power	170 Watts
Physical	
Length	6.93 in
Diameter	3.73 in
Weight in Water (with 1m cable)	0.75 lb
Propeller Diameter	3.0 in (Twin Blade)

Appendix 6:

Date: January 11, 2016

SANTA CLARA UNIVERSITY
ME 195 -- ADVANCED DESIGN II
Winter 2016

PARTS LIST

Design Project: Marine Autonomous Research Vessel (MARV)

Subsystem	Component Description	Part #	# of items	B/M/O /D[1]	Vendor	Cost / part	Responsible person	Hours[2]	Order or start date	Receive or finish date
Bridge										
	1”, 2ft long 8020 Extrusion	AL01	5	B	McMaster	$8.35	B, G, D, S	4	11/24/15	11/25/15
	1”, 4ft long 8020 Extrusion	AL02	3	B	McMaster	$14.20	B, G, D, S	2	11/24/15	11/25/15
	90º Plate, 3” Long, 1” Tall*	AL03	3	B	McMaster	$8.47	B, G, D, S	0.5	11/24/15	11/25/15
	Bracket, 2” Long, 1” Tall*	AL04	4	B	McMaster	$5.85	B, G, D, S	0.5	11/24/15	11/25/15
	Locking Pivot, 1” Tall*	AL05	4	B	McMaster	$18.98	B, G, D, S	1	11/24/15	11/25/15
	Handle, 1” Tall*	AL06	2	B	McMaster	$6.40	B, G, D, S	0.25	11/24/15	11/25/15
	End-cap, 1”*	AL07	10	B	McMaster	$1.20	B, G, D, S	0.5	11/24/15	11/25/15
	Tee Bracket, 1” Tall*	AL08	2	B	McMaster	$8.83	B, G, D, S	0.5	11/24/15	11/25/15
	Steel End Feed Fastener*	AL09	2	B	McMaster	$2.30	B, G, D, S	0.25	11/24/15	11/25/15
	Spring Loaded Ball Fastener*	AL10	2	B	McMaster	$1.12	B, G, D, S	1	11/24/15	11/25/15
	3-Way External Connector*	AL11	4	B	McMaster	$9.86	B, G, D, S	1	11/24/15	11/25/15
	Mounted 1” Ball Bearing	AL12	2	B	McMaster	$50.80	B, G, D, S	2	1/7/16	1/8/16
	Tube Holder, 1” *	AL13	4	B	McMaster	$36.12	B, G, D, S	2	1/7/16	1/8/16
	Heavy Duty Hinge, 1” *	AL14	2	B	McMaster	$20.57	B, G, D, S	1	1/7/16	1/8/16
	12” Long Brace *	AL15	2	B	McMaster	$17.15	B, G, D, S	0.5	1/7/16	1/8/16
	Bridge Assembly	**BA1**	**1**	**M**	-	**$422.46**	B, G, D, S	**17**	11/24/15	1/15/16
Pontoon										
	4’ x 8’ 5052 Aluminum Sheet, 0.080”	P01	1	B	Gorilla Metals	$148.36	B, G, D, S	1.5	1/6/16	1/8/16
	5052 Aluminum 10” Cylinder**	P02	2	O,D	Ray L. Helwig Plumbing & Heating	$0	B, G, D, S	2	1/11/16	1/25/16

	Component Description	Part #	# of items	B/M/O /D[1]	Vendor	Cost/part	Responsible Person	Hours[4]	Order or Start Date	Receive or Finish Date
	5052 Aluminum Nose Cone**	P03	2	O,D	Ray L. Helwig Plumbing & Heating	$0	B, G, D, S	5	1/11/16	1/25/16
	5052 Aluminum End Cap**	P04	2	O,D	Ray L. Helwig Plumbing & Heating	$0	B, G, D, S	1	1/11/16	1/25/16
	Aluminum Angle Bracket 1"	P05	2	O,D	Gorilla Metals	$16.50	B, G, D, S	0.5	1/6/16	1/8/16
	Pontoon Assembly	**PA1**	**2**	**M**	-	**$164.86**	B, G, D, S	**10**	1/11/16	1/29/16
Electronics										
	Chirp Sonar	E01	1	D	MBARI	$0	B, G, D, S	4	10/24/15	2/1/16
	Intel Edison Microcontroller	E02	1	D	RSL	$0	B, G, D, S	10	7/12/15	7/13/15
	3DR Pixhawk	E03	1	D	RSL	$0	B, G, D, S	10	10/24/15	10/25/15
	RobotEQ Motor Driver	E04	1	D	RSL	$0	B, G, D, S	4	10/24/15	10/25/15
	BlueRobotics T200 Marine Thruster	E05	2	B	Blue Robotics	$249.00	B, G, D, S	2	12/18/15	12/23/15
	DC Motor - Steering	E06	1	B	Blue Robotics	$70.00	B, G, D, S	2	1/5/16	1/15/16
	3DR GPS Module	E07	2	D	RSL	$0	B, G, D, S	3	10/24/15	10/25/15
	3DR Telemetry Module	E08	2	D	RSL	$0	B, G, D, S	1.5	10/24/15	10/25/15
	Electronics Assembly	**EA1**	**1**	**M**	-	**$319.00**	B, G, D, S	**36.5**	10/24/15	2/14/15Tes
Page Totals			**61P/4A**			**$906.32**		**63.5**		

---

* Attachments that fit 1" 8020 T-slotted Aluminum extrusion

** Manufactured by outside organization

[1] B = bought, M = made by you, O = made by others, D = donated

[2] Total team hours in design, procurement, manufacture, and assembly

Appendix 7:

Fluids Analysis of MARV:

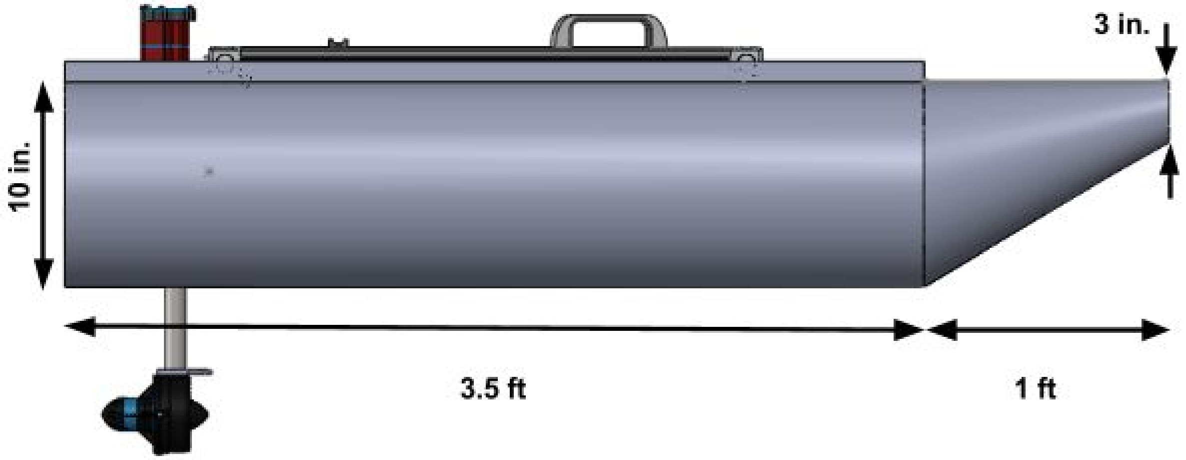


Figure 43: Dimensions of a single pontoon.

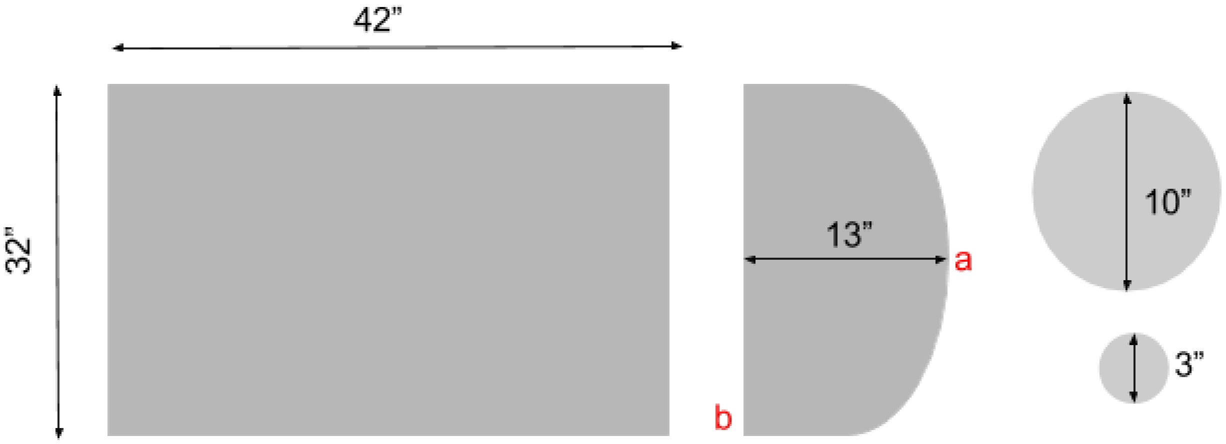


Figure 44: Pontoon dimensions of raw material before manufacture.

Table 17: List of constants used in preliminary pontoon payload calculations.

Quantity	**Value**
Length of Cylinder, L_c	3.5 feet
Length of Nose Cone, L_N	1 foot
Diameter of Pontoon, D	10 inches
Thickness of Pontoon, T	0.080 inches

Weight of Aluminum per ft^2 , W_{Al}	1.1174 lb/ft^2
Density of Water	0.0361 lb/in^3

Weights [1] :

$$W_{cylinder} = 2\pi R_{cylinder} L_{cylinder} W_{Al}$$
$$= 2\pi(5'')(3.5')(1.1174\ lb/ft^2)(1/12) = 10.24\ lb$$
$$W_{cone} = \tfrac{1}{2}\pi ab W_{Al}$$
$$= 0.5(\pi)(13'')(32'')(1.1174\ lb/ft^2)(1/144) = 5.07\ lb$$
$$W_{end\ cap} = \tfrac{\pi}{4} D^2 W_{Al}$$
$$= \tfrac{\pi}{4}(10'')^2(1.1174\ lb/ft^2)(1/144) = 0.55\ lb$$
$$W_{total} = W_{cylinder} + W_{cone} + W_{end\ cap}$$
$$= 10.24 + 5.07 + 0.55 = \mathbf{15.9\ lb}$$

Total Area [1] :

$$A_{total} = A_{cylinder} + A_{cone} + A_{end\ cap} = 2\pi R_{cylinder} L_{cylinder} + \tfrac{1}{2}\pi ab + \tfrac{\pi}{4} D^2$$
$$= 2\pi(5'')(3.5')(1/12) + 0.5(\pi)(13'')(32'')(1/144) + \tfrac{\pi}{4}(10'')^2(1/144) = 14.25\ ft^2$$
$$A_{end\ cap} = \tfrac{\pi}{4}(10'')^2 = 78.54\ in^2$$

Surface Area in Contact with Water at Given Depths[1] :

1. At 33% Submerged:

$$A_{33\%} = 0.33 A_{end\ cap} = 0.33(78.54\ in^2) = 25.9\ in^2$$

2. At 50% Submerged:

$$A_{50\%} = 0.50 A_{end\ cap} = 0.50(78.54\ in^2) = 39.3\ in^2$$

Buoyancy of Pontoons[1] :

$L_{total} = L_{cylinder} + L_{cone} = 3.5\ ft + 1\ ft = 4.5\ ft$, $*L_{total}$ is used for simplicity

1. At 33% Submerged:

$B_{33\%}$[1] $= L_{total}\rho_{water} A_{33\%} = (4.5\ ft)(0.0361\ lb/in^3)(25.9\ in^2)(12) = 50.5\ lb/pontoon$

2. At 50% Submerged:

$$B_{50\%} = L_{total}\rho_{water} A_{50\%} = (4.5\ ft)(0.0361\ lb/in^3)(39.3\ in^2)(12) = 76.6\ lb/pontoon$$

Total Load Supported by Two Pontoons[1] :

1. At 33% Submerged:

$$F_{max_{33\%}} = 2(B_{33\%} - W_{33\%})$$
$$= 2(50.5\ lb\ -\ 15.9\ lb) = \mathbf{69.2\ lb}$$

2. At 50% Submerged:

$$F_{max_{50\%}} = 2(B_{50\%} - W_{50\%})$$
$$= 2(76.6\ lb - 15.9\ lb) = \mathbf{121.4\ lb}$$

Surface Area[1] :

$$SA = \Pi r^2$$
$$SA = (\Pi)(5")^2$$
$$SA = 78.54 in^2 = 0.051 m^2$$

Drag Force Per Pontoon[1] :

$$F_D = \tfrac{1}{2}\rho v^2 C_D A$$
$$F_D = (\tfrac{1}{2})(1{,}000\tfrac{kg}{m^3})(1\tfrac{m}{s})^2(1.2)(0.051 m^2)$$
$$F_D = 30.6\ N = 6.88\ lbf$$

Table 18: Parameters utilized in calculating drag force of initial pontoons

Variable	**Value**
Density of Fluid, ρ	$1{,}000\ \frac{kg}{m^3}$
Velocity of Fluid, v	$1\ \frac{m}{s}$
Coefficient of Drag, C_D	1.2
Surface Area, A	$0.051\ m^2$
Drag Force, F_D	30.6 N = 6.88 lbf

Table 19: CFD Results Compared to Worst Case Hand Calculation

Variable	**Value**
Total Worst Case Drag Force (Hand Calculation)	$13.76\ lbf$
Total CFD Drag Force (Z-direction)	$5.04\ lbf$

Area of Pipe [2]:

$$A = \tfrac{\Pi}{4}(D^2 - d^2)$$
$$A = \tfrac{\Pi}{4}(1^2 in^2\ -\ 0.624^2 in^2)$$
$$A = 0.480\ in^2 = 0.00031\ m^2$$

Moment of Inertia [2] : $(I_x = I_y = I)$

$$I = \tfrac{\Pi}{64}(D^4 - d^4)$$
$$I = \tfrac{\Pi}{64}(1^4\ in^4 - 0.624^4 in^4)$$
$$I = 0.04165 in^4 = 1.733x10^{-8} m^4$$

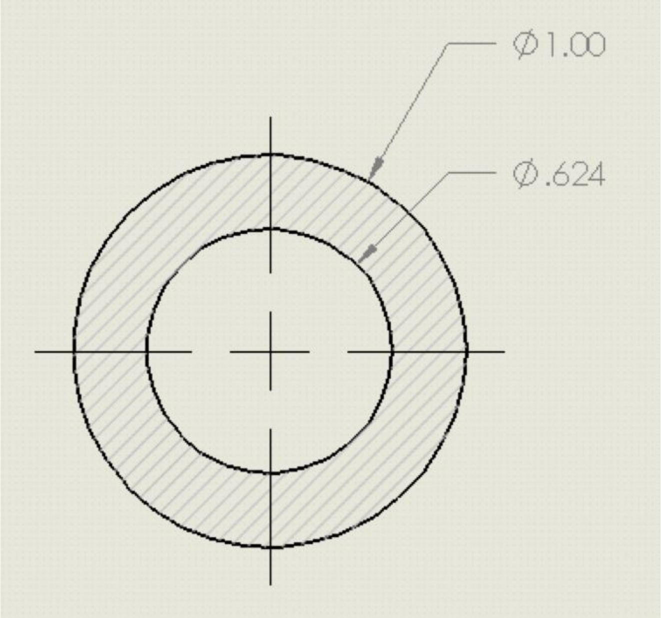


Figure 45: Cross-section of Steering Column

Table 20: Material - 6061 Aluminium

Mechanical Properties and Physical Dimensions	**Values**
Outer Diameter (OD), D	1 in
Inner Diameter (ID), d	0.624 in
Wall Thickness	0.188 in
Area, A	0.480 in^2 = 0.00031 m^2
Moment of Inertia, I	0.04165 in^4 = $1.733x10^{-8}m^4$
Modulus of Elasticity, E	69 GPa

Drag force experienced by the pipe [2]:

$$A_{rect} = r * h$$
$$A_{rect} = 5\ in * 20\ in$$
$$A_{rect} = 100in^2 = 0.065m^2$$

$$F_D = \tfrac{1}{2}\rho v^2 C_D A$$
$$F_D = (\tfrac{1}{2})(1,000\tfrac{kg}{m^3})(1\tfrac{m}{s})^2(0.47)(0.065m^2)$$
$$F_D = 15.275\ N = 3.44\ lbf$$

Table 21: Parameters utilized in calculating drag force of initial pontoons.

Variable	**Value**
Density of Fluid, ρ	1,000 $\frac{kg}{m^3}$
Velocity of Fluid, ν	1 $\frac{m}{s}$
Coefficient of Drag, C_D	4.7
Rectangular Projected Area, A_{rect}	0.065 m^2
Drag Force, F_D	15.275 N = 3.44 lbf

Steering Column Modeled as Cantilever Beam with Uniformly Distributed Load (water)

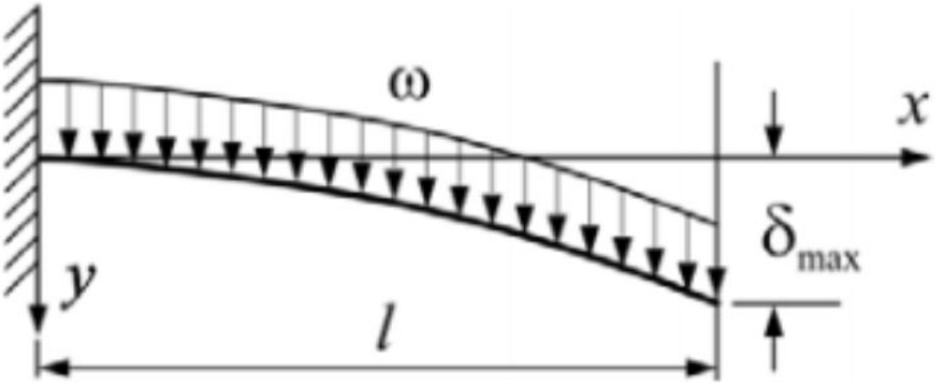


Figure 46: Cantilever Beam with Uniformly Distributed Load

Uniformly Distributed Load [2]:

$$\omega = \frac{Load}{Length\ of\ Contact}$$

$$\omega = \frac{15.275\ N}{0.51m}$$

$$\omega = 29.95\ \frac{N}{m}$$

Cantilever beam deflection from uniformly distributed load [2]:

$$\delta_{max} = \frac{\omega l^4}{8EI}$$

$$\delta_{max} = \frac{(29.95\ \frac{N}{m})(0.51m)^4}{(8)(69\ x\ 10^9 Pa)(1.733\ x\ 10^{-8} m^4)}$$

$$\delta_{max} = 2.118\ x\ 10^{-4} m$$

$$\delta_{max} = 0.2118\ mm$$

Table 22: Variables utilized to calculate maximum beam deflection under uniformly distributed load

Variable	**Value**
Uniformly Distributed Load, ω	$29.95\ \frac{N}{m}$
Length of Beam, l	$0.51\,m$
Modulus of Elasticity 6061 Aluminum, E	69 GPa
Moment of Inertia, I	$1.733 \text{ x } 10^{-8}\ m^4$
Maximum Beam Deflection, δ_{max}	$0.21\ mm$

Appendix 8:

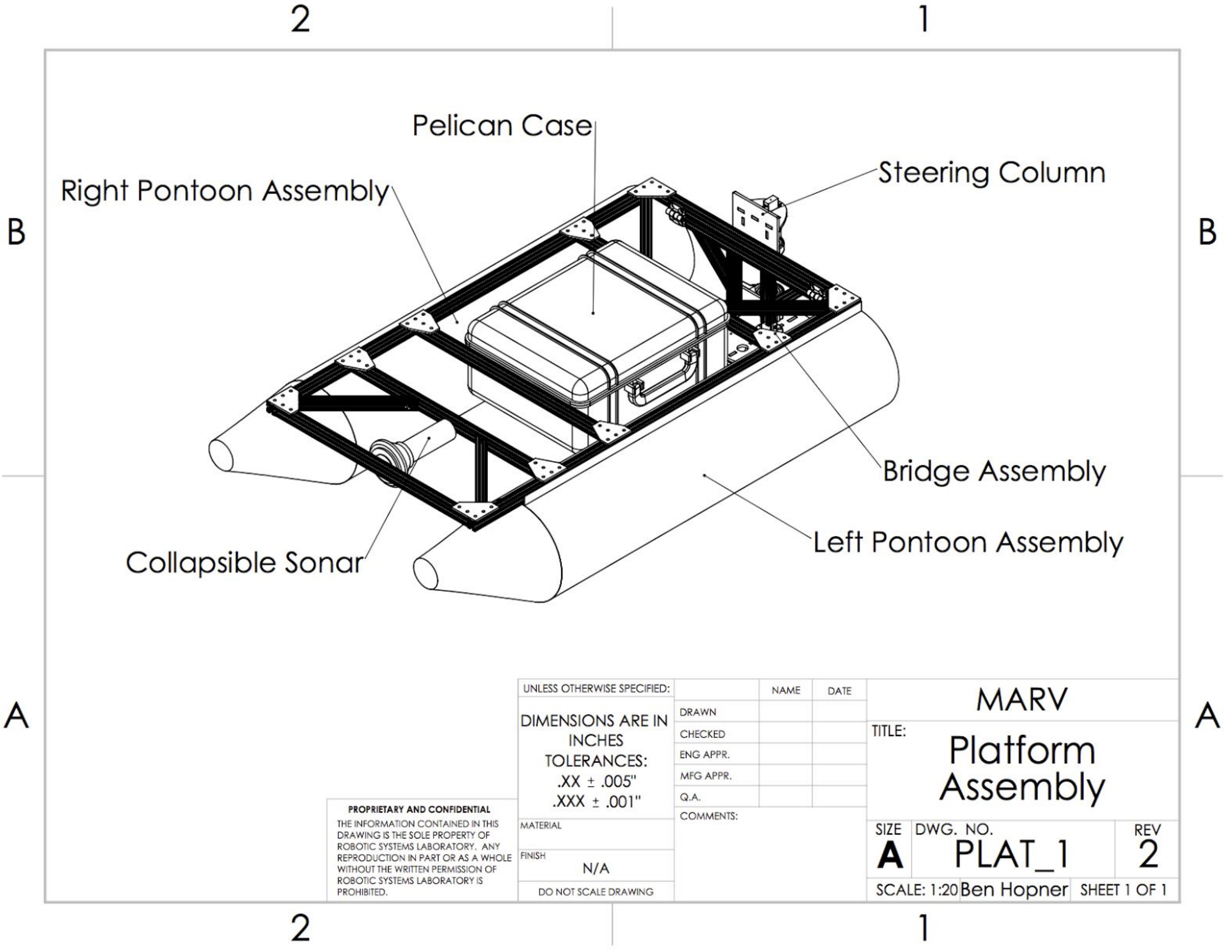


Figure 47: Solidworks drawing of MARV assembly.

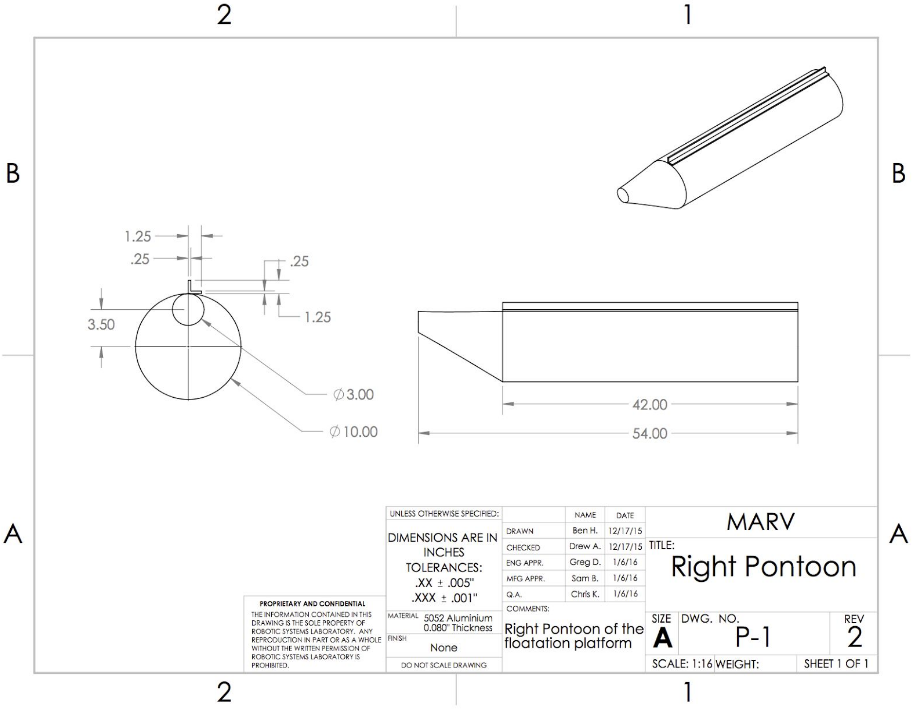


Figure 48: Right pontoon Solidworks drawing.

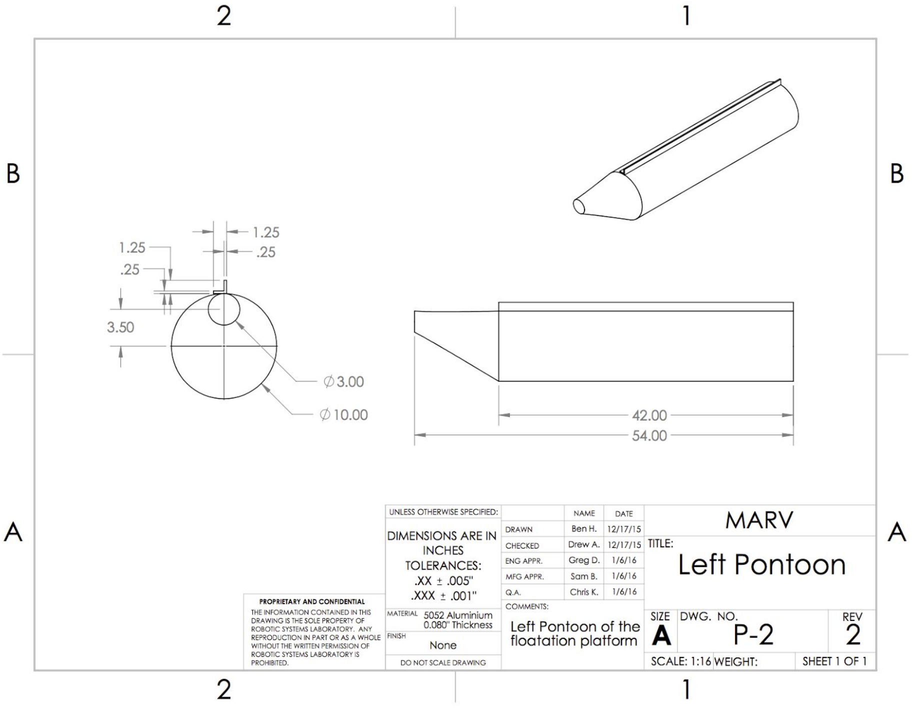
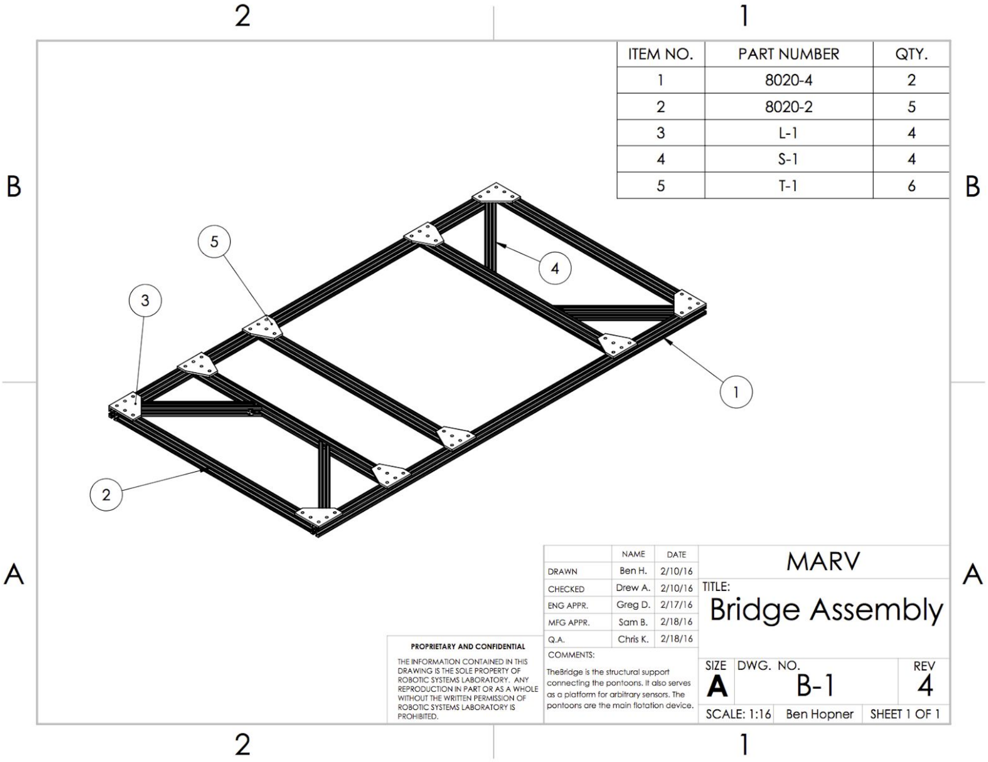


Figure 49: Left pontoon Solidworks drawing.



ITEM NO.	PART NUMBER	QTY.
1	8020-4	2
2	8020-2	5
3	L-1	4
4	S-1	4
5	T-1	6

	NAME	DATE
DRAWN	Ben H.	2/10/16
CHECKED	Drew A.	2/10/16
ENG APPR.	Greg D.	2/17/16
MFG APPR.	Sam B.	2/18/16
Q.A.	Chris K.	2/18/16

MARV

TITLE: Bridge Assembly

COMMENTS:
TheBridge is the structural support connecting the pontoons. It also serves as a platform for arbitrary sensors. The pontoons are the main flotation device.

PROPRIETARY AND CONFIDENTIAL

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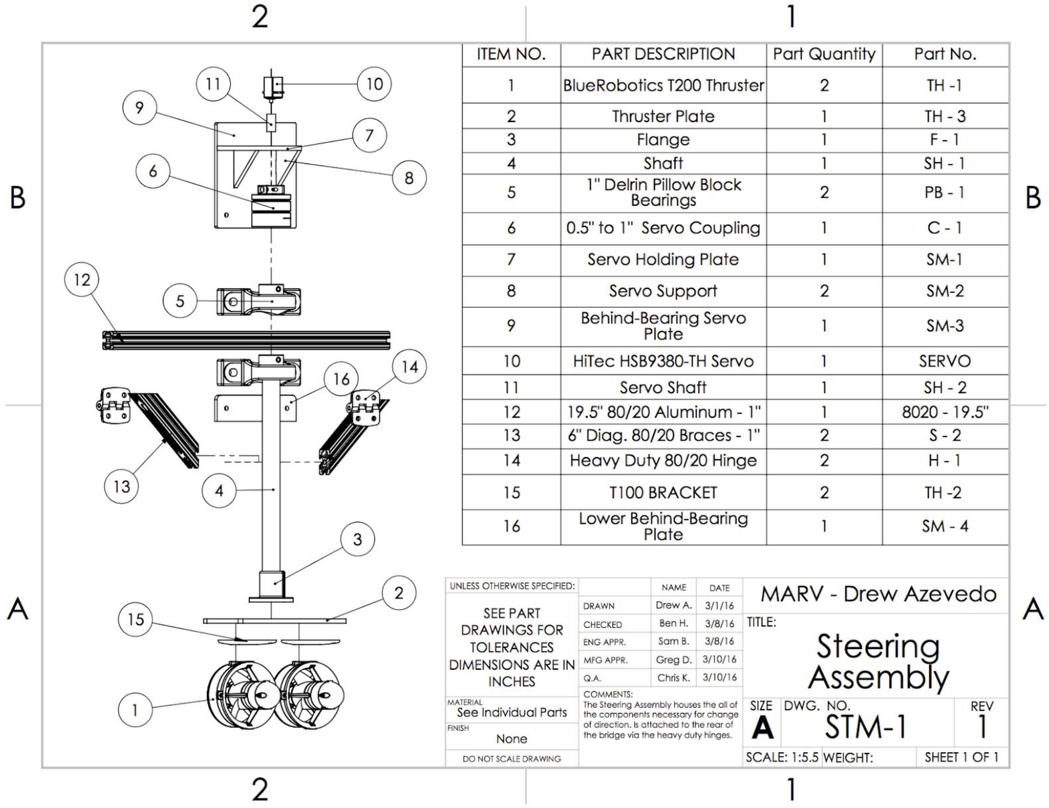
SIZE A DWG. NO. B-1 REV 4

SCALE: 1:16 Ben Hopner SHEET 1 OF 1

Figure 50: Bridge Assembly Solidworks drawing.



ITEM NO.	PART DESCRIPTION	Part Quantity	Part No.
1	BlueRobotics T200 Thruster	2	TH -1
2	Thruster Plate	1	TH - 3
3	Flange	1	F - 1
4	Shaft	1	SH - 1
5	1" Delrin Pillow Block Bearings	2	PB - 1
6	0.5" to 1" Servo Coupling	1	C - 1
7	Servo Holding Plate	1	SM-1
8	Servo Support	2	SM-2
9	Behind-Bearing Servo Plate	1	SM-3
10	HiTec HSB9380-TH Servo	1	SERVO
11	Servo Shaft	1	SH - 2
12	19.5" 80/20 Aluminum - 1"	1	8020 - 19.5"
13	6" Diag. 80/20 Braces - 1"	2	S - 2
14	Heavy Duty 80/20 Hinge	2	H - 1
15	T100 BRACKET	2	TH -2
16	Lower Behind-Bearing Plate	1	SM - 4

UNLESS OTHERWISE SPECIFIED:

SEE PART DRAWINGS FOR TOLERANCES DIMENSIONS ARE IN INCHES

MATERIAL See Individual Parts

FINISH None

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Drew A.	3/1/16
CHECKED	Ben H.	3/8/16
ENG APPR.	Sam B.	3/8/16
MFG APPR.	Greg D.	3/10/16
Q.A.	Chris K.	3/10/16

COMMENTS:
The Steering Assembly houses the all of the components necessary for change of direction. Is attached to the rear of the bridge via the heavy duty hinges.

MARV - Drew Azevedo

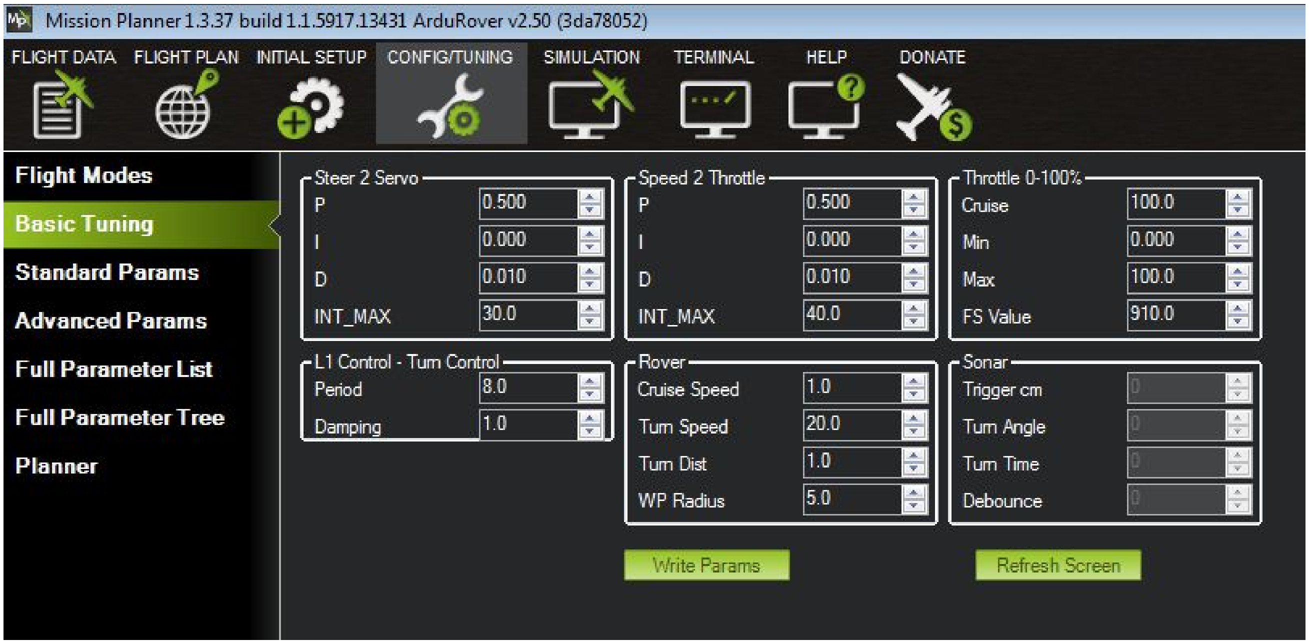
TITLE: Steering Assembly

SIZE A DWG. NO. STM-1 REV 1

SCALE: 1:5.5 WEIGHT: SHEET 1 OF 1

Figure 51: Steering column assembly drawing.

Appendix 9:



Steer 2 Servo	
P	0.500
I	0.000
D	0.010
INT_MAX	30.0

Speed 2 Throttle	
P	0.500
I	0.000
D	0.010
INT_MAX	40.0

Throttle 0-100%	
Cruise	100.0
Min	0.000
Max	100.0
FS Value	910.0

L1 Control - Turn Control	
Period	8.0
Damping	1.0

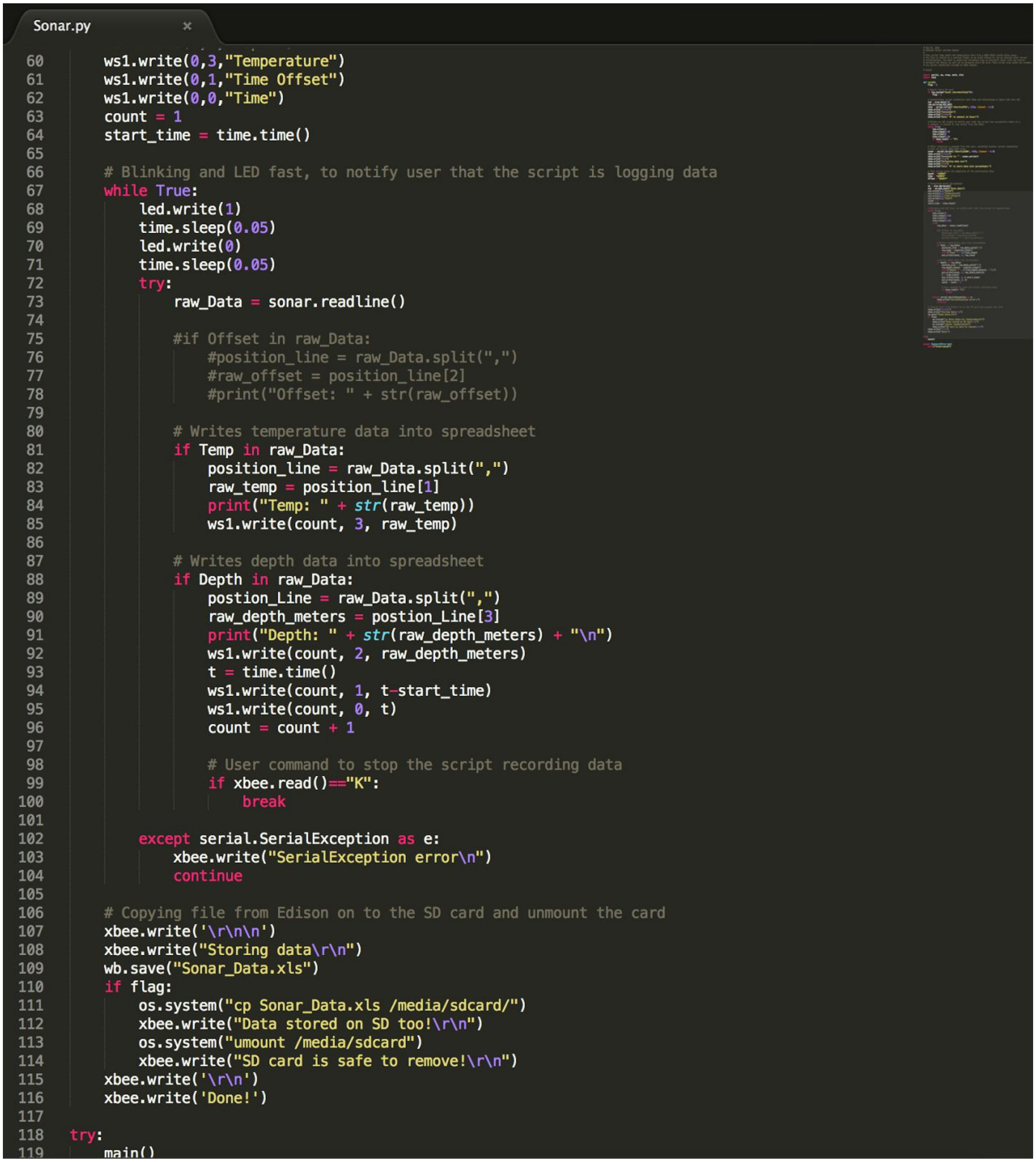
Rover	
Cruise Speed	1.0
Turn Speed	20.0
Turn Dist	1.0
WP Radius	5.0

Sonar	
Trigger cm	0
Turn Angle	0
Turn Time	0
Debounce	0

Figure 52: Mission Planner Control Parameters

Appendix 10:

(a)



```python
    ws1.write(0,3,"Temperature")
    ws1.write(0,1,"Time Offset")
    ws1.write(0,0,"Time")
    count = 1
    start_time = time.time()

    # Blinking and LED fast, to notify user that the script is logging data
    while True:
        led.write(1)
        time.sleep(0.05)
        led.write(0)
        time.sleep(0.05)
        try:
            raw_Data = sonar.readline()

            #if Offset in raw_Data:
                #position_line = raw_Data.split(",")
                #raw_offset = position_line[2]
                #print("Offset: " + str(raw_offset))

            # Writes temperature data into spreadsheet
            if Temp in raw_Data:
                position_line = raw_Data.split(",")
                raw_temp = position_line[1]
                print("Temp: " + str(raw_temp))
                ws1.write(count, 3, raw_temp)

            # Writes depth data into spreadsheet
            if Depth in raw_Data:
                postion_Line = raw_Data.split(",")
                raw_depth_meters = postion_Line[3]
                print("Depth: " + str(raw_depth_meters) + "\n")
                ws1.write(count, 2, raw_depth_meters)
                t = time.time()
                ws1.write(count, 1, t-start_time)
                ws1.write(count, 0, t)
                count = count + 1

                # User command to stop the script recording data
                if xbee.read()=="K":
                    break

        except serial.SerialException as e:
            xbee.write("SerialException error\n")
            continue

    # Copying file from Edison on to the SD card and unmount the card
    xbee.write('\r\n\n')
    xbee.write("Storing data\r\n")
    wb.save("Sonar_Data.xls")
    if flag:
        os.system("cp Sonar_Data.xls /media/sdcard/")
        xbee.write("Data stored on SD too!\r\n")
        os.system("umount /media/sdcard")
        xbee.write("SD card is safe to remove!\r\n")
    xbee.write('\r\n')
    xbee.write('Done!')

try:
    main()
```

(b)

```python
try:
    main()

except KeyboardInterrupt:
    print("Interrupted")
```

(c)

Figure 53: Python script running serial data collection and storage.