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Buoyant Unmanned Distress Detection and Evacuation (BUDD-E) System

A Major Qualifying Project

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Degree of Bachelor of Science

by

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Abstract

An average of 3,533 people die of drowning each year in the United States of America (USA), despite advances in lifeguarding and rescue technique, and the widespread public awareness of the importance of water safety. Many more drowning victims survive but are left with lasting brain injury because of prolonged oxygen deprivation, and over half of these incidents take place in natural water settings such as lakes, beaches, and rivers. Swimmers in distress typically have 20 to 60 seconds before drowning, and the primary challenge in rescuing distressed swimmers or drowning victims lies in initially identifying the need for assistance from land before it is too late. The Buoyant Unmanned Distress Detection and Evacuation (BUDD-E) System provides lifeguards and emergency responders with a cost-effective and state-of-the-art solution to identifying and rescuing victims in these challenging environments. The BUDD-E System monitors swimmers' locations and pulses with convenient wristbands worn by each individual. The custom circuitry designed for the wristband is equipped with an emergency trigger to indicate that a swimmer requires help, but in case they are unable to do this, the system can also analyzes the pulse and position data to detect swimmers in distress. This information is relayed through specially designed signal relay buoys anchored at regular intervals along the beach to send the data to a processor on the beach, which prepares information for on-duty lifeguards as a live map of swimmers' locations, color coded to indicate their safety status. In emergency situations, an unmanned robotic platform is dispatched to victims immediately for support, and is able to transport a conscious victim or an unconscious victim and lifeguard to shore. With a comprehensive response system in place, the BUDD-E System aims to prevent unnecessary loss of human life and minimize trauma associated with drowning incidents by complimenting and augmenting the efforts of trained rescue personnel.

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Acknowledgements

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Finally, the BUDD-E System team wishes to thank Worcester Polytechnic Institute for creating the environment of learning and engineering excellence that encouraged the team's growth from enthusiastic high school students into burgeoning engineers entering industry.

CHAPTER 1 – DROWNING PREVENTION AT USA BEACHES

1. Introduction

The United States Center for Disease Control reports that over 3,800 individuals die each year from unintentional drowning in the USA, and another 5,700 individuals are hospitalized, without including boating accidents and natural disasters (*Drowning - United States, 2005-2009*, 2012). It is unacceptable that 9,500 drowning incidents occur on an annual basis. The BUDD-E System aims to prevent drowning deaths and minimize the risk of sustained injuries to drowning victims. Over half of drowning incidents take place in natural water settings such as lakes, rivers, and beaches (*Unintentional Drowning: Get the Facts*, 2012), and the BUDD-E System is designed to be installed at public and private beaches. With limited methods of approach, dynamic currents, lack of underwater visibility, and the proportion of beachgoers to lifeguards, beachfront environments present the most complex situation to monitor and respond to. The BUDD-E System is designed to address this matter and to significantly reduce and even eliminate drowning incidents at locations where it is implemented.

The BUDD-E System has two primary functions in environments at which it is installed. The first is to monitor swimmers safety in the water and communicate this to lifeguards, while the second is to rapidly assist in rescue efforts when needed. Two-dimensional triangulation is used to locate individuals who are in distress, using signals broadcast from a wearable wristband that is encoded with the swimmer's pulse. In addition, each wristband is equipped with a manual-activation switch so that a swimmer may signal a need for help. The wristband transmits an acoustic signal that is relayed by a network of buoys to a central processor on land. The relay buoys consist of a receiver located on the surface of the water, custom circuitry that filters and amplifies the signal, and then a simple radio antenna. Once the signal reaches the processor, it is used to calculate where the distressed individual is located. From that point, the latest position data is sent to an autonomous robotic boat that navigates coastal environments at speeds of up to 20 miles per hour. The navigation software utilizes a combination of GPS data and obstacle positions, broadcast by the rest of the system, which are then confirmed en route using onboard SONAR. Upon reaching a distressed swimmer, the robot can approach to safely provide flotation assistance. This is in contrast to a lifeguard who would otherwise put themselves at risk of injury while assisting. The robot's design allows it to reach swimmers faster than a human rescuer. Even if the robot reaches a victim after they fall unconscious, a lifeguard can use the robot as a marker to quickly find the victim. They can then lift the victim onto the robot for rapid transport to land for lifesaving procedures. To compliment this procedure, a mobile application communicating the status and location of swimmers using an interactive map is provided to keep lifeguards apprized in real-time.

The report that follows details the methods involved in the BUDD-E System's design and creation. Chapter Two details the topics researched necessary for the completion of the system. Chapter Three contains the methodology for the design of the BUDD-E System, and concludes with the procedures followed to construct the custom circuitry and robot prototypes. Chapter four consists of the BUDD-E System's final design and explores the performance of the robot, the relay buoys, the main processing system, and the wristband worn by swimmers. Additionally it contains recommendations for future development of the BUDD-E System.

CHAPTER 2 – DROWNING, RESCUE, AND WATERCRAFT DESIGN

2. Introduction

The BUDD-E System creates a unique junction in subject areas that otherwise do not often intersect. The technical aspects of the project range from path-finding algorithms to the specifics of boat hull design. The circuitry designs required by the BUDD-E System to operate were very ambitious, and required a thorough grounding in signal filtering, physical limitations in acoustic signal transmission and reception, and power systems to name a few key concepts. In conjunction with research about various means of aquatic propulsion, characteristics of the many types of rechargeable batteries, and the Newtons per Volt specifications of drive motors, it was crucial to research and obtain a working command of modern lifeguarding practices and existing solutions to problems encountered in day-to-day recreational swimming environments.

2.1 Project Motivation and Problem Introduction

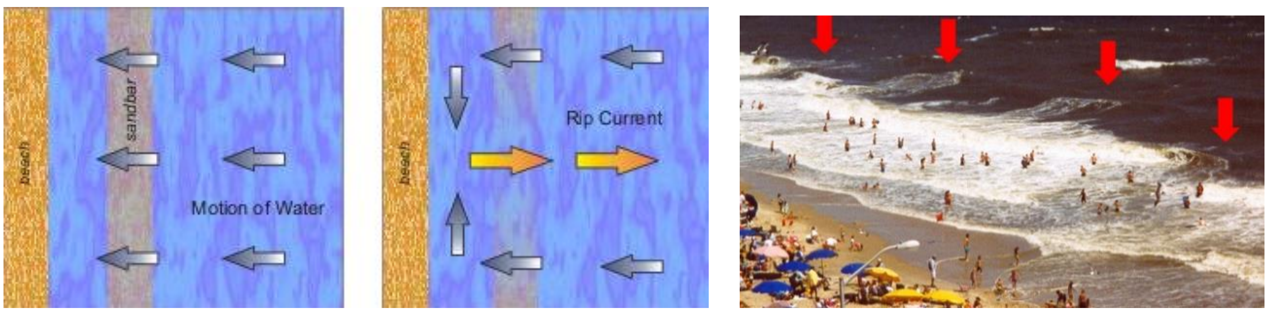
The overarching goal of this project was to enhance a lifeguard's ability to detect and quickly respond to drowning victims. This section will discuss an overview of current drowning statistics in the United States of America (USA) as well as modern approaches to lifeguarding as a response. These approaches include the primary challenges for lifeguards, and the best efforts to address them in practice. Finally, this section will conclude with a short discussion on differences and similarities between the BUDD-E System and the Emergency Integrated Lifesaving Lanyard (EMILY).

2.1.1 Drowning

Drowning is the "process of experiencing respiratory impairment from submersion/immersion in liquid," and accounts for 7% of all injury related deaths globally (World Health Organization, 2012). While Drowning is not always fatal, it is the 3rd most prevalent cause of unintentional injury death on a global scale, 5th in the USA, and the 2nd leading cause of unintentional injury death for children from 1-14 years of age (*Unintentional Drowning: Get the Facts*, 2012). On average in the USA, 3,533 people die from unintentional non-boating drowning incidents each year – this means that each day 10 people drown and die on average, and two of them are children. Furthermore, 5 children require emergency department care for nonfatal injuries for every child whose injuries prove fatal (*Unintentional Drowning: Get the Facts*, 2012). These statistics are alarming, and demonstrate a clear need to a comprehensive solution to drowning prevention.

2.1.2 Challenges of Swimming Safety in Open Water

The most common locations for drowning incidents to occur are bathtubs, swimming pools, and natural bodies of water. A study of fatal drowning incidents between 2005 and 2009 found that 51% took place in natural environments such as rivers and beaches (Center for Disease Control and Prevention, 2004). While the most effective means of drowning prevention in controlled environments (bathtubs, pools) is close supervision. Natural environments present a more complex situation; there are added risk factors because of changing beach topography, tides, currents, and limited means of approach for lifesaving personnel. A swimming pool, for example, is a controlled body of water typically surrounded on all sides by easy means of entry



A. Rip current overhead diagram B. Rip currents at a crowded beach

Figure 1 - Rip current illustrations

and exit. In contrast, a coastal beach is a complicated dynamic system of waves, changing water levels, shifting sediment, and unpredictable phenomena such as rip currents. Rip currents, as shown in Figure 1, are strong currents moving perpendicularly away from land. Rip currents form as tidal activity effects the flow of receding waves, and create channels through narrow gaps between sand bars near the coastline. They are a particular problem on surf beaches, and over 80% of all water rescues at USA surf beaches are due to rip currents (National Weather Service Southern Region Headquarters).

On top of the environmental complications of swimming in natural bodies of water, lifesaving personnel are only able to reach drowning victims from the beach, so the farther out a victim is swimming, the longer it will take for a rescuer to reach them. Compared to the more optimal means of reaching a victim at a typical pool, this means a lifeguard has even less time to notice a victim once they require assistance. Attempting to rescue drowning victims in natural locations also exposes responders to the same hazards that may have caused the victim's predicament in the first place. As a result, these situations are more difficult for lifeguards or other lifesaving personnel to respond to with successful outcomes.

2.1.3 Lifeguarding Challenges

The lifeguard-training manual established by the American Red Cross identifies three categories of swimmers that require special attention from lifeguards: distressed swimmers, active drowning victims, and passive drowning victims. A distressed swimmer will characteristically have his or her head above water and be able to breathe, but may not have the breath to call for help. Additionally, the swimmer in distress will be decreasingly able to maintain this behavior or to make forward progress through the water to safety. At this stage, the swimmer can grab onto and use flotation devices, but without this or other intervention, will become a drowning victim. Active drowning victims will not be able to consistently keep their mouths above the water's surface, and are not able to gesture or call for help. As a result, even active drowning victims are often difficult to identify, and typically can only stay near the water's surface for 20 to 60 seconds at the most. In some cases, swimmers can lose consciousness and are then considered passive drowning victims. They are unable to keep themselves above water due to injury, illness, or intoxication, and require immediate intervention by lifesaving personnel. It is noted that even with careful observation it can be impossible to see underwater in waterfront environments, and this makes these environments even more crucial for constant monitoring of swimmers in the area (American Red Cross, 2013).

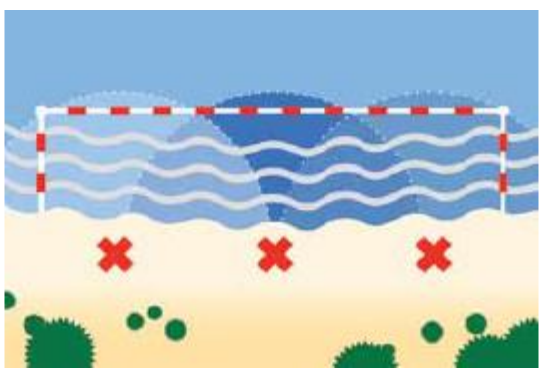


Figure 2 - Lifeguard scanning zones at a waterfront

The Red Cross defines a process for effective scanning of swimming environments in the cited manual, but notes that there are many challenges to be overcome. Most notably, lifeguards are deterred by monotony, fatigue, distractions, blind spots, heavy or low patron loads, high air temperature, and an inability to see through the water due to glare, surface distortion, or murky water. In situations where a drowning victim could be struggling and pass out in as few as 20 seconds, it is crucial that a lifeguard be constantly vigilant. For an example of how difficult this may be, consider how frequently most automobile drivers check rear and side-view mirrors and blind spots when driving along a smooth, straight road. It is human nature to relax without an impetus for action, and for a lifeguard, this is not an option. As much as various studies and organizations have attempted to standardize procedures to reduce the chances of error in this component of lifeguard performance, it remains the most significant source of error in lifeguard duties.

2.1.4 EMILY

A commercially available product that has saved lives since 2010 is EMILY. EMILY remains an emergency response technology rather than an emergency prevention technology. It is capable of moving through water at 28 miles per hour, and is remotely controlled by emergency response personnel. It is equipped with sonar to detect and slow down around obstacles directly in front of it (primarily to avoid collisions with swimmers). While EMILY is able to reach a drowning victim much faster than a lifeguard, and is able to tow a conscious swimmer through the water, it is unstable in the water unless the swimmers are holding on precisely as shown in Figure 3.

Figure 3 - EMILY, being driven across the ocean (Calderin, 2010)

This is a step in the right direction, but it is not enough to completely ensure the safety of swimmers. In contrast, the BUDD-E System focuses on empowering lifeguards to be constantly aware of the status of swimmers by monitoring their pulses and relaying that data and their positions on a clear map of their designated area. In the event that a swimmer requires assistance, the BUDD-E robot is automatically deployed directly to the victim to maximize the chances of providing support. Not only does its buoyant stability enable a drowning victim to grab it from any direction and use it for support, but should it be required, the victim can climb completely out of the water and ride to shore on the BUDD-E robot. If a victim is unconscious, a lifeguard can bring the victim onto the robot and immediately begin CPR while they are driven back to shore. By combining preventative measures with timely comprehensive emergency response, the BUDD-E System will make lakes and beaches safe for everyone.

2.2 Hull Design

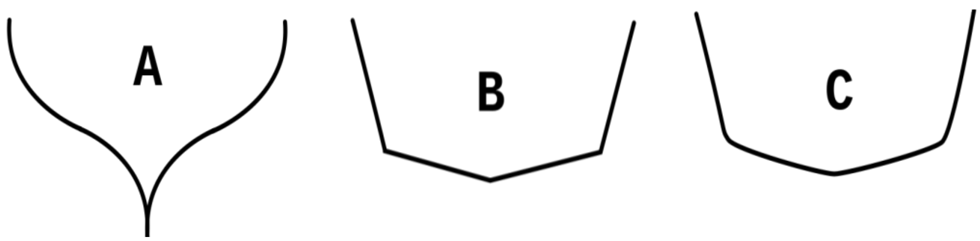
Ship design has several components that must be considered to create a properly hulled craft. There is no hull shape that is always right, but instead there are different types that work best in different situations. In designing ship hulls it is important to factor in what the vessel is going to be used for, how it will be propelled, what kind of environment it will operate in and what materials are available. Ship design has been around for many millennia; simple log rafts have been used for over 10,000 years (Figure 4).

Figure 4 - Simple log raft (Navigator, 2014)

These were designed following the principle of buoyancy; materials less dense than water, like wood, float. The first truly "hulled" watercraft is currently believed to come from Ancient Egypt. Their ships were built with wood planks tied together and sealed with reeds. (Ward, 2006) The vast majority of boats, and certainly all boats before the motorboat, are displacement boats. The hull creates a cavity in the water and the displacement lifts the craft. As other civilizations developed similar craft, methods of shipbuilding progressed, resulting in sturdier ships with better sail technology.

For many centuries, the lack of sufficient navigation technology limited the ability of ships to brave the open ocean and reliably return. During the Renaissance period, a breakthrough in sail technology allowed ships to sail closer to the wind which meant truer courses could be taken. Additionally, the development of several navigational tools allowed for ships to begin sailing farther distances more accurately. The next major advancement in watercraft was moving away from wind power towards engines powered by coal, fuel, and electricity. The original coal powered steam boats didn't move much faster than a ship with the wind in its sails, but steam power was more reliable. With the genesis of the motorboat in 1883, previously impractical hull designs could be implemented (Daimler, 2012).

Wind powered ships rarely had the wind directly behind them, which means that they had a certain degree of force blowing them sideways. To counteract this, shipbuilders created ships with s-shaped hulls and large keels (Figure 5A). While this approach was effective at reducing



A. S-bottom hull B. Hard Chine C. Soft Chine

Figure 5 - Hull types (Wikipedia, 2014)

drift, the hull shape limited the hydrodynamic efficiency of the vessel.

Planing and semi-planing hulls were developed to take advantage of motorized power (Figure 5 B&C). A pure planing hull does not cut through the water like a displacement hull, but instead rides on top, using hydrodynamic forces to keep itself from settling. Semi-planing hulls split the difference between displacement and planing. At speed, the craft supports its weight partially from displacing water and partially from the force of the water pushing against the hull.

2.2.1 Design of a Trimaran

To choose a hull type for the autonomous life-saving robot, a set of design goals must be identified. The most important of these is speed. If the robot cannot get to the distressed swimmer in time, all other design requirements are rendered pointless. Secondary to speed is stability/seaworthiness – the craft must be able to support the load of the saved victim on its outside edge and not roll. Three options were considered: a generic hull riding on hydrofoils, a mono-hull, or a multi-hull. The hull's advantages and disadvantages are presented in Table 1.

As seen in Table 1, Hydrofoils have the necessary speed to get to the targeted location. A mono-hull design could work, however for a moderate price increase, the multi-hull design holds more advantages, namely, speed/efficiency and stability. Low drag means more speed with lower power output, which leads to higher efficiency. Stability becomes important due to the small size of the robot. It may have a comparatively large load far from its center of buoyancy when a victim grabs on it and it needs to remain upright. Also, the size of ocean waves in comparison to the craft necessitates a higher buoyancy, which a multi-hull design provides.

Table 1 – Advantages and Disadvantages of Different Hull Types

	Advantages	Disadvantages
Hydrofoils	• Fastest • Efficient	• High maintenance • Safety issues • Maneuverability • Must obtain target speed to plane
Mono-hull	• Simple • Cheap • Maneuverable	• Tendency to roll • Deep waterline • Not very fast
Multi-hull	• Faster • Efficient • Very Stable • Low waterline	• Maneuverability • More expensive than mono-hull

Catamarans and trimarans are the two common forms of multi-hull designs. While penta-hull designs do exist they are rare. Trimaran and catamaran boats can be sail or engine powered, with powered catamarans being more common than powered trimarans. The inherent weight on the extremity of the craft from a saved victim could seriously unbalance a catamaran of minimal size. A centrally driven trimaran could maintain better stability with this imbalanced weight, making it the better choice. With a hull shape in mind, additional design parameters were imposed. No onboard passengers for any significant distance simplifies a host of design points. Passenger comfort is a non-issue, and the hull of the boat can be completely sealed against water. This allows for an aggressive, wave-piercing design, not usually feasible for a craft this size due to the amount of water that will wash over the craft. The scale of the craft to the waves also factors into the choice of a wave piercing design. While trimarans have great stability, the small craft will have issues with large rolling waves and maintaining a sense of speed.

2.2.2 Materials for Constructing Ship Hulls

The main components of the vessel can be broken down into the hull, body and the internal structure. The role of each component guides the material selection, as each needs to meet certain requirements to perform correctly. The hull directly interacts with the water and constantly pounds against the waves. It is also going to take the brunt of the force of interaction with rocks, sandy beaches, or submerged objects. This means that the hull must be strong enough to withstand impacts, tough enough to withstand large scratches and tearing action, yet be flexible enough to not shatter. Most vessels focus on maximizing internal storage space, and therefore the "body" of the ship is often simply air. However, since the trimaran needs little storage space, filling the body with a hard, closed cell foam creates a foam boat with a tough shell to prevent damage. The internal structure of the trimaran will consist of cross-beams or ribs that help to distribute forces from across the hull, allowing it to withstand larger impacts. As the design is intended to be wave-piercing, increased strength around the bow will be essential.

2.2.3 Forces and Moments Acting on a Hull

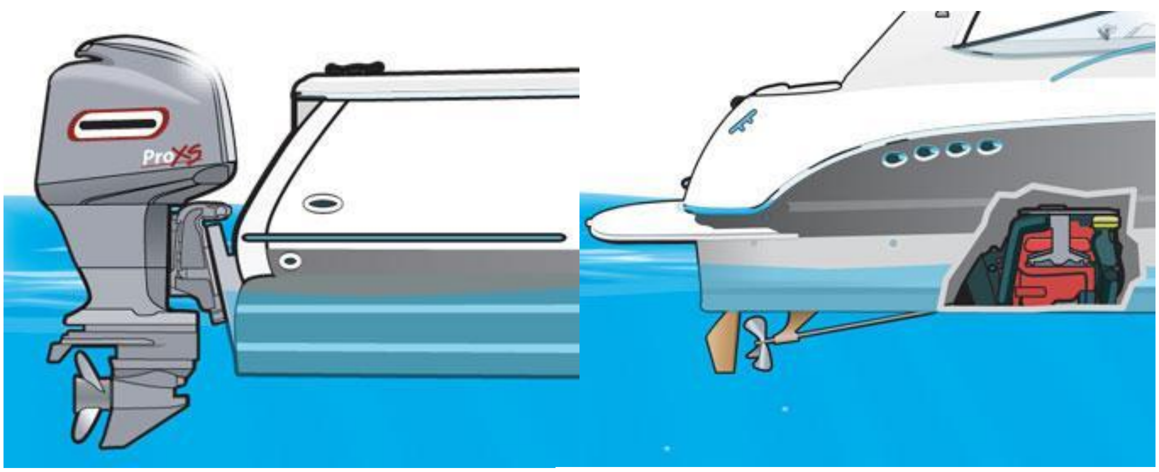
There are many forces to be considered when designing a boat. Three main categories exist: hydrodynamic forces, environmental disturbances and forces and moments due to actuators. (Yan & Jianda) Hydrodynamic forces are applied to anything involving moving water and consist of radiation-induced damping forces and moments due to gravity, skin friction, wave drift damping and vortex shading. It also includes the hydrodynamic resistance of the surrounding fluid. Environmental disturbances are forces and moments relative to what kind of water the object is operating in. Examples of these include ocean currents, waves, wind, Froud-Kriloff forces, diffraction forces, and viscous forces. The third category is forces and moments due to actuators. This category is present for any object operating in or out of water. For the trimaran, the two forces in this category are propeller thrust and rotary rudder moment (Yan & Jianda).

2.3 Methods of Movement

There are a number of methods of propulsion available to watercraft. One of the oldest methods is externally powered, using the wind and a sail to move. Sailing does have the distinct disadvantage of not being self-reliant, as there may be no wind to be moved by. Thus self-propulsion is vastly preferred for most boats. The major distinction for the purposes of this project then comes down to what method of propulsion and how it will be powered, either combustion or electrically.

2.3.1 Exposed Drive

An "exposed drive" system is one such that the propeller is outside of the hull of boat. This is the simplest and most common form of powered aquatic propulsion. In full sized boats, exposed drive systems are primarily broken up into inboard and outboard configurations. An outboard system like that shown in Figure 6A, contains the propeller and the motor in one single unit, which is then attached to the boat. An inboard system, as seen in Figure 6B, keeps the motor inside the hull, connecting to the propeller with a long drive shaft.



A – Outboard Motor (Boat-ed.com) B – Inboard Motor (Boat-ed.com)

Figure 6 - Outboard and Inboard Motors

Outboard motors are easily accessible and can be easily maintained or removed and replaced with a new one. They do tend to be more expensive than inboard motors, but require less maintenance overall, as they are designed as one contained unit. Conversely, inboard motors are not one self-contained unit, and can be much larger and are much more customizable. In addition, since they only output a drive shaft into the water, they generate much lower drag forces. This results in a cleaner overall appearance than an outboard motor.

2.3.2 Rim Driven Thruster

A rim-driven thruster is a recently developed alternative to a standard exposed propeller. On a standard propeller, the blades emanate from the center, where they attach to the drive shaft. As shown in Figure 7, Rim-driven thrusters have blades that extend from an outer ring, pointing inwards. They have no central hub, meaning that they are more hydro-dynamically efficient than

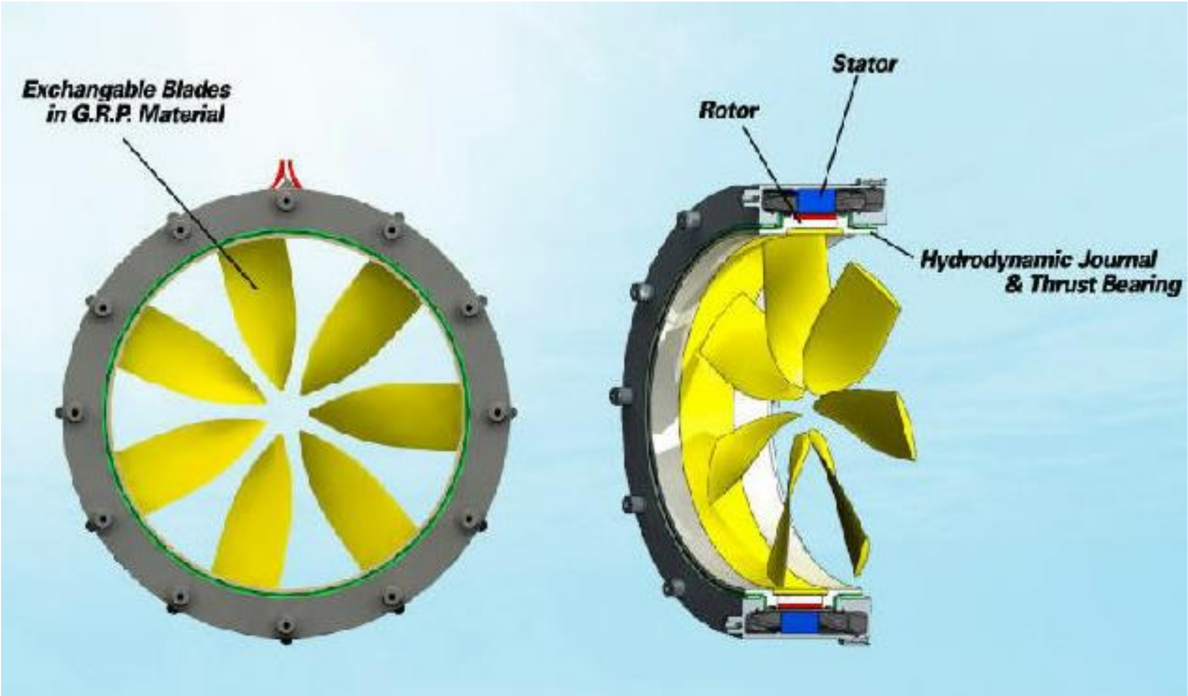


Figure 7 - Diagram of a Rim-Driven Thruster (YachtForums.com)

a standard propeller and are less susceptible to floating debris. In the case of electrically powered motors, the rim driven thrusters cannot easily match the power available from standard gas powered configurations. To match the same level of power output, they require very large electric motors and massive amounts of battery. This limitation often relegates them to use as directional thrusters, used for small motions and precise positioning more than forward movement. To be viable as the main source of propulsion in large-scale boats, a hybridized system would be necessary, using a combustion engine to produce electric current for the rim driven thruster. In smaller scale applications, the rim driven thruster would be viable with current battery technology, sans any form of combustion engine. Due to their fairly recent development, however, they remain quite expensive at any scale.

2.3.3 Jet Drive

Jet drives work by drawing in water through an inlet grate on the bottom of the vessel's hull and forcing it out a rear-facing nozzle using an impeller. As illustrated in Figure 8, jet drive systems have no external moving parts other than a directional nozzle. This reduces the chance of a swimmer accidentally being injured.

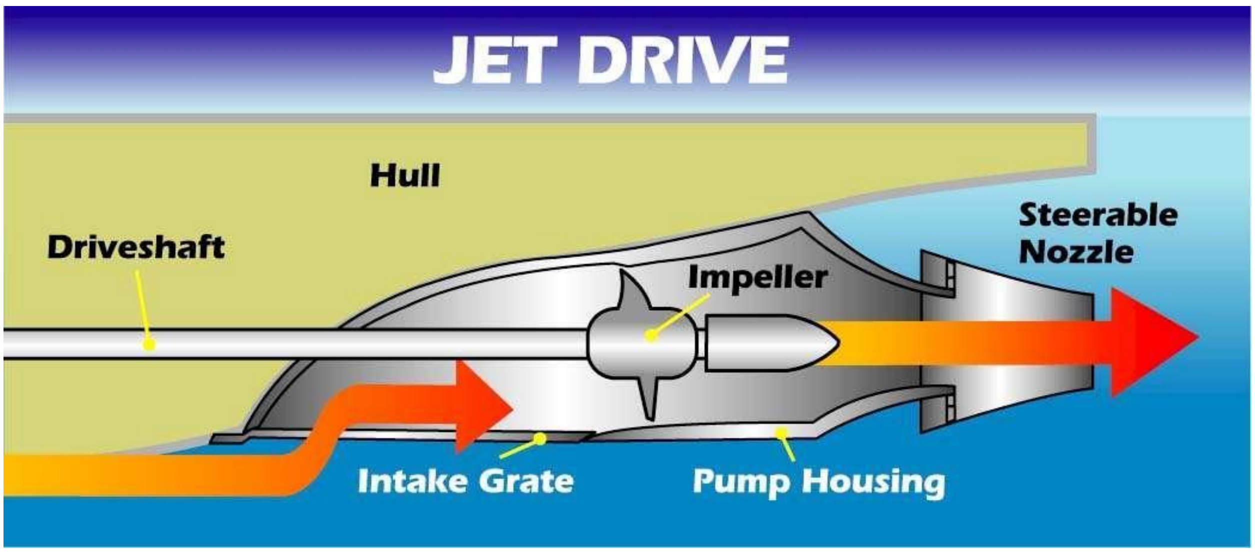


Figure 8 - Diagram of a Jet Drive (Mauinow.com)

The intake is flush-mounted with bottom of the hull so without the protrusions of other means of propulsion, jet drive vessels have a much lower drag than alternatives. These vessels also have a much shallower draft. Draft is a term for the depth that a boat sits in the water. The shallower its draft, the less water it needs to float freely.

2.4 Motor Selection

To power the propulsion system of a boat, there are two major categories to select from. These are combustion engines and electric motors. Combustion engines include gas engines, in which the fuel is ignited by a spark plug, and diesel engines, where the compression of the air in the motor generates enough heat to ignite the fuel. Electric engines are either brushed or brushless, depending on the construction of the motor. Hybrid systems also exist, with a combustion engine generating power for the electric motor, instead of powering it off of batteries. For a small-scale boat, purely electrical systems are the most sensible choice, being very easily scalable and having very little impact on the environment around them, unlike combustion engines, which have exhaust gases to be considered.

2.4.1 Brushed Motors

Brushed motors are simple and durable, require a minimum of electronic control, and work well in nearly any environment. These motors have been in use for over 100 years, and are easily maintained. The basic method of construction, with labeled components, is shown in Figure 9 below. The major parts of the motor are the commutator, the brushes, the armature and the ring of permanent magnets. The brushes are used to provide power to the armature, through

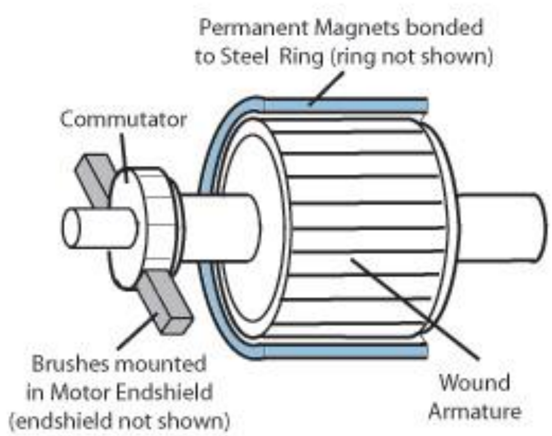


Figure 9 - Components of a Brushed Motor (OrientalMotor)

their connection with the commutator. This connection is not fixed, and the brush maintains friction contact with the commutator through spring pressure. This type of contact allows the commutator and armature to rotate freely while still receiving power.

When the coil of copper wire wound around the armature is powered, it generates an electrical field. This electric field causes the armature to rotate, pushing the left side coil away

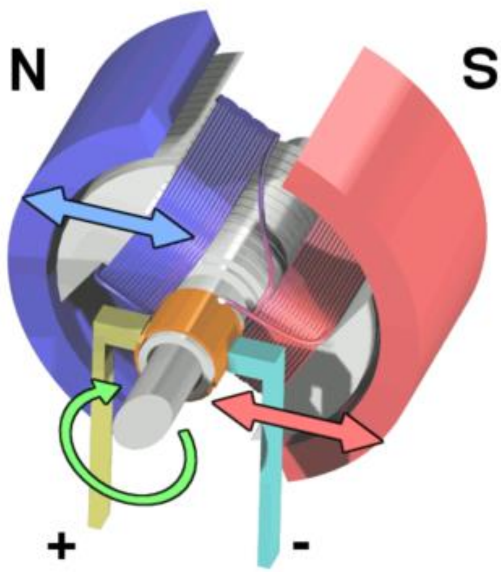


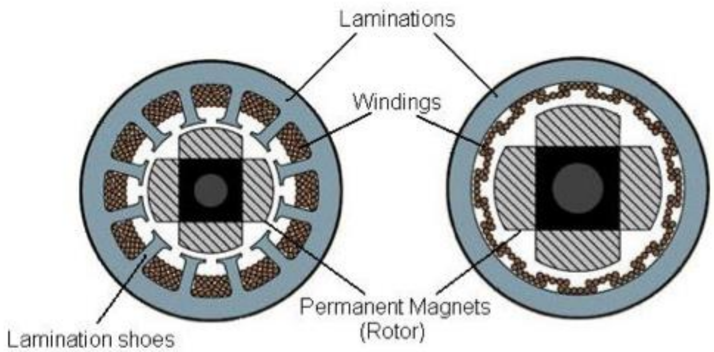
Figure 10 - Brushed Motor in Cycle (Wikipedia)

from the left side magnet, as illustrated in Figure 10. As the neutral middle point between left and right sides is reached the commutator reverses the current, continuing the spin. The brushes are the points of contact for the commutator, allowing it to receive incoming power and still rotate freely. They are the most common maintenance item for brushed motors, as they wear out over time.

2.4.2 Brushless Motors

Compared to brushed motors, brushless motors have many advantages. They are more efficient, in both torque-to-weight ratio and torque-to-power ratio. Brushless motors are also quieter, both in audible sound and by producing a lower amount of Electromagnetic Interference (EMI). Because of how they can be cooled they can be sealed, which potentially leads to a longer, more reliable lifespan. They are more complex, and as such are much more expensive. They also require more complex electronics for adequate control, as their function is timing based instead of being simply voltage-dependent.

Brushless motors function in a similar manner to brushed motors, but inversed. Instead of a wire-wrapped armature being fed current, rotating inside a ring of permanent magnets, in a brushless motor the armature is covered in magnets and the windings are located in the exterior



A. Slotted Motor B. Slotless Motor

Figure 11 - Brushless Motor Diagram (Network)

ring around the magnets. There are two basic types of brushless motors, slotted, shown in Figure 11A, and slotless, shown in Figure 11B. The primary difference between the two is cost of manufacture and efficiency. As alluded to in the name, the design of brushless motors means that there is no need for the motor to have brushes, and a more direct connection from the power to the electric field generating coils can be established. Having coils placed externally also means that brushless motors can be cooled with conduction, allowing them to be fully sealed from the environment. As with brushed motors, the current must be switched constantly to rotate the motor. Brushless motors often achieve this behavior with the aid of microcontrollers, as communication with electronics allow for more flexible designs.

2.5 Electrical Power

Power for the electric motors either comes from onboard batteries or from a hybrid combustion system, as discussed earlier. As a purely electrical system is a better fit for this project, background on the batteries that may be used to supply power are required. Battery types are widely varied in efficiency and cost, and battery technology is constantly improving, especially as the demand for hybrid and fully electric vehicles increases. Research on this subject ranges from the cheapest, most common battery type, Lead Acid, to one of the newest, Lithium Iron Phosphate.

2.5.1 Explanation of Terms

In their most basic form, batteries have 3 major components; the cathode, the anode and the electrolyte. The cathode and the anode are the positive and negative terminals respectively, and the electrolyte serves to separate them inside the battery. When fully charged, the anode has a higher amount of electrons than the cathode. These electrons want to move to the cathode in order to balance the electrical difference. This movement is shown in Figure 12 below. The

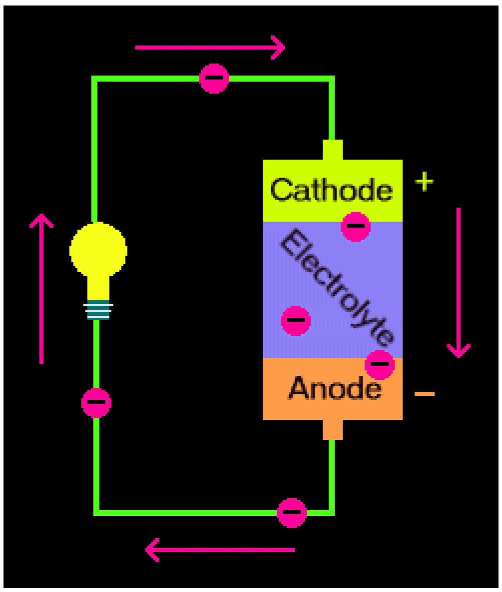


Figure 12 - Flow of Electrons in a Battery
(Qualitative Reasoning Group)

electrolyte stops the electrons from being able to this directly however, enabling the long-term storage of energy in the form of this unbalance. When a circuit is hooked up to a battery, the electrons travel from the anode, through the circuit, to the cathode, powering the circuit along the way.

The amount of charge that a battery can hold is dependent upon its internal composition. As the electrons reposition in the battery, the anode and the cathode both undergo an electrochemical change, after which the battery can no longer supply power. Recharging a battery is simply supplying another power source to reverse the process, returning the anode and cathode back to their original states.

2.5.2 Lead Acid

Lead acid batteries are among the oldest types of batteries, and are most commonly used in cars. They are low in energy density, but are able to supply high-surge currents, making them ideal for the starting of cars and other engine driven vehicles. They are sometimes used outside of high-surge applications largely because they are much cheaper than newer battery technologies. Lead acid batteries have a useful life of 500-800 cycles (PowerSonic, 2011).

2.5.3 Ni-MH

Nickel-Metal Hydride batteries (abbreviated Ni-MH), are most commonly used as rechargeable AA and similarly sized batteries for consumer electronics. They have higher energy density, power density, and specific energy than Lead Acid batteries, but they suffer from high self-discharge rates. Careful study has shown that they may lose as much as 15% of their charge per month[1]. Lower Self-Discharge (LSD) variants exist, but they sacrifice significant amounts of capacity to lower the rate. Ni-MH batteries have useful lives of 500-1000 cycles (Panasonic Corporation, 2014).

2.5.4 Li-Ion

Lithium-Ion batteries are commonly used in rechargeable electronics like home phones and cordless power tools. They offer better energy density, power density, and specific energy than Ni-MH batteries, along with considerably lower self-discharge rates. They are more complex batteries, and are more expensive as a result. Lithium-Ion batteries are also more dangerous, as they are pressurized and subject to potential combustion if overheated or improperly charged since their electrolyte is flammable. Their useful cycle life is in the 400-1200 range (Thermoanalytics, 2014). Lithium-Ion is actually a term for a family of batteries, grouped together because of the manner in which they work. As the batteries discharge, lithium ions move from the cathode to the anode; this process is reversed when the batteries are charging.

2.5.5 Li-Po

Lithium Polymer batteries are an evolution of Li-Ion batteries, substituting charge capacity for reduced manufacturing costs, improved reliability, and adaptability to packaging shapes. This comes from using a polymer to hold the electrolyte instead of an organic solvent. Many cell phone and laptop batteries are Li-Po, where a low weight and energy density are more crucial than the increased costs. They require specialized chargers and protective circuitry to maintain safe operation, as they have the potential to explode if overcharged, and can have their capacity lowered if they are over-discharged. Multi-cell battery packs also require a balancing circuit to ensure that all of the cells charge and discharge evenly. Their cycle life is claimed to be in 400 – 600 range, depending on how the battery is built (Thermoanalytics, 2014).

2.5.6 LiFePO4

Lithium Iron Phosphate batteries are a recent technology; when compared with other Lithium batteries, they have a lower specific energy and energy density. This is a tradeoff for increased power density and a vastly more stable battery, both chemically and thermally. While it is still possible to misuse one to the point of combustion, the use of iron in the cathode makes it considerably more difficult to do so. Lithium Iron Phosphate batteries also have a much longer usable life than most others, offering 2000-3000 cycles depending on construction. This cycle life can be extended significantly with the use of protective circuits that regulate how it is discharged (Electropaedia, 2005).

2.6 Wireless Communication and Electronic Systems

Since water is an incompressible fluid, underwater wireless communication have only one viable option, and that is to use compressions waves, like acoustic waveforms, for communication. Though acoustic waves are the best way to wirelessly communicate underwater there is still a plethora of problems, which are exaggerated by the speed and the nature of the compression wave. The frequency that the waveforms are emitted at is a key aspect when designing any type of communication system due to tradeoffs between higher and lower frequencies. Higher frequencies have the ability to transmit a greater amount of data, while lower frequencies can travel greater distances underwater.

The most common problem that is encountered in designing an underwater communication system is dealing with interference. Most interference comes in the form of noise, not sensor noise but additional physical sound waves. These sound waves can come from any source and can even be an exact copy of the signal that has reflected off of the ocean floor. The other main problem that is encountered with underwater acoustic waveforms is that they are characterized as doubly spread. This means that the waveforms are spread out in both the time and frequency domain.

2.6.1 Problems With underwater Acoustics

Underwater acoustic communication is one of the more unforgiving and difficult wireless communication mediums because it is severely band limited in both the higher and lower ends of the frequency spectrum. It can be classified into three different categories depending on range; long, medium, and short range. For long range systems operating between 10km and 100km, the available bandwidth is roughly 1 to 2 kHz. The medium ranged systems, between 1 km and 10 km, have a bandwidth that is slightly less than 10 kHz. The short range systems that operate at a range of less than 1 km has an available bandwidth of greater than 10 kHz. Though for the systems that operates in the extremes, both long and short, the bandwidth that is capable of being used in those systems are also in the extreme range. For systems that need an extreme distance, those exceeding 1000 km, the available bandwidth is less than 1 kHz. For systems that only require distances of less than 100m the available bandwidth peaks up at over 100 kHz (Robert S. H. Istepanian, 2002). As seen in the information above, the range that a system needs to communicate in dramatically affects how much bandwidth that the system has to operate with.

Table 2 is a breakdown of the ranges of frequencies that acoustic waveforms can travel through water. The table references the information that is above; range is defined in length by the distance section of the table. Bandwidth is the available range of frequencies that can travel the corresponding distance.

Table 2 - The Distances that the waveforms can travel dependent on their frequency.

Range	**Distance** (km)	**Bandwidth** (kHz)
Long Range	10-100	1-2
Medium Range	1-10	10
Short Range	<1	100

Though range is the key factor in restricting the bandwidth of a system, there are three other factors that contribute to how sound wave propagate through water and affect the waves; signal to noise ratio or SNR: frequency, energy loss, and interference. At high frequency sound waves traveling through water have a higher absorption rate and at lower frequencies there is a vast increase in the energy level of noise interference, from both natural and manmade sources.

In Figure 13, one will notice that distance and frequency are inversely related to the SNR. To a certain extent, the shorter the signal travels and the lower the frequency the higher the SNR.

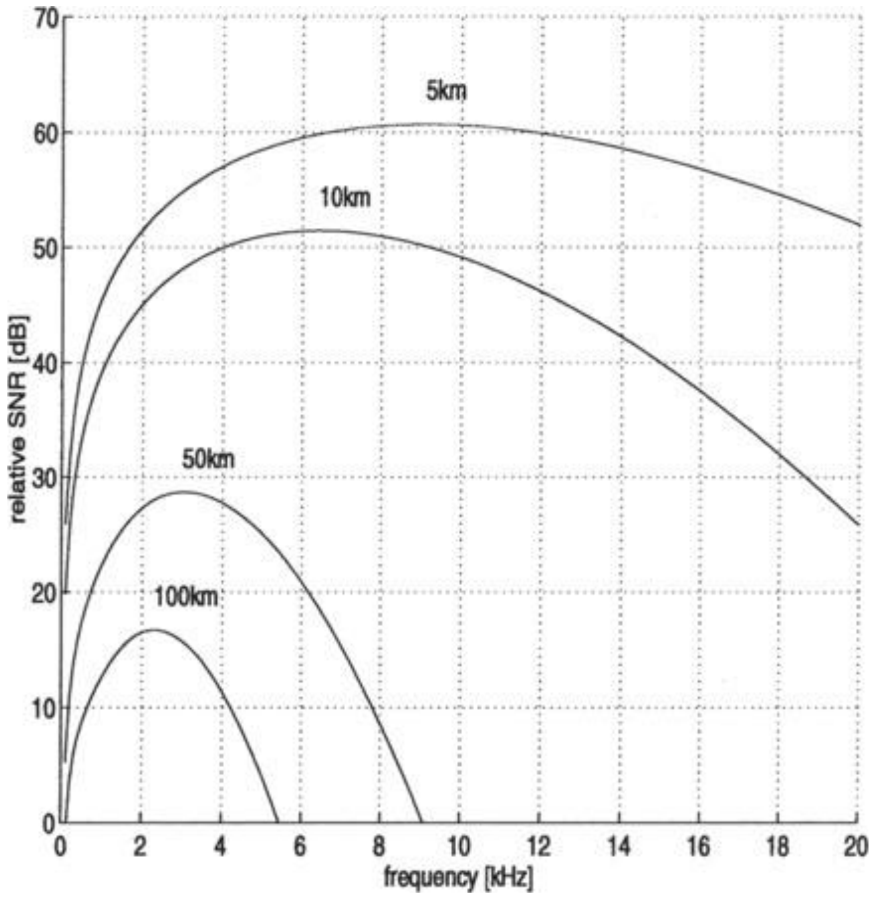


Figure 13: Frequency-dependent portion of SNR (Robert S. H. Istepanian, 2002)

The SNR of a signal directly relates to its ability to be able to be received and identified as the signal, not just noise. Every receiver will pick up noise in addition to the desired signal, but the higher the SNR, the stronger the incoming signal will be compared to the noise that the receiver picks up. A high SNR is evident by the fact that the signal will have a greater amplitude than the received noise. Energy loss of a signal is highly dependent on the propagation distance that the signal will travel. Since sound waves are compressions, energy loss happens mainly in two different ways: transmission loss and energy spreading.

When sound moves it sends water molecules crashing into other water molecules - which results in less and less energy in every water molecule as the wave moves further from its point of origin, as seen in Figure 14. This is transmission loss. Energy spreading occurs when the wave propagates outward; as the radius of the wave increases the overall surface area of the wave increases. Thus, as the radius of the wave increases, the number of water molecules impacted also increases. As the number of water molecules increases the amount of energy per molecule decreases, according to the principal of conservation of energy.

There is an abundance of different sources of interference in different types of water; these interferences can come from both natural and manmade sources. The main type of interference that is present underwater is sound interference or compression waves. Sound

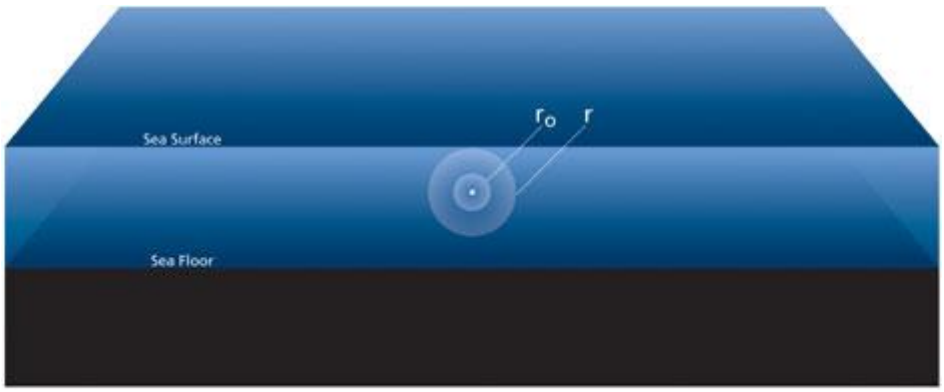


Figure 14: The effect propagation distances has on the energy of a wave

interferes with the desired signal by both interfering with the signal directly and by interfering with the hard ware. Compression waves, like any other waves, are subject to interference from other waves. This happens when the two waves superimpose over each other. When this happens the resulting waves amplitude is the sum of the two waves. This can result in a variety of different waveforms and can also result in dead zones.

Hardware sound interference comes in two different types, unwanted sound from the environment and the sound that is naturally present in the electrical system, due to the electrical charge from the flow of electrons. The types of sound that hardware, like a hydrophone, would pick up are dependent on the location of the hardware. Deep ocean noise is predominantly ambient noise. It could originate from a large cruise ship, whales, or a fish swimming near the equipment. In shallow and coastal water, the noise that is most common is manmade. Beaches will have an abundance of noise from people splashing in the water and harbors will have noise that is generated by ships cruising through.

Another problem that has to be addressed when planning underwater communications is the delay in receiving the signal. Most communication systems depend on electromagnetic signals which travel at the speed of light (299,792,458 m/s), and therefore the delay is negligible. In water, the speed of sound is 1500 m/s, and while this is an improvement over the 340 m/s that sound travels in air, there can still be a noticeable delay. This means that any type of remote controlled underwater vehicles (UV) communicating with the surface must have some level of autonomy.

The Doppler Effect is the phenomenon in which the frequency of a waveform will change depending on its motion with respect to the receiver. When the transmitter and the receiver are moving away from each other the waveform that is being emitted will have a lower frequency and vice versa. In essence, the Doppler Effect will spread the signal out in the frequency domain. This can cause problems for the system when it tries to filter out the desired signal. The filter is

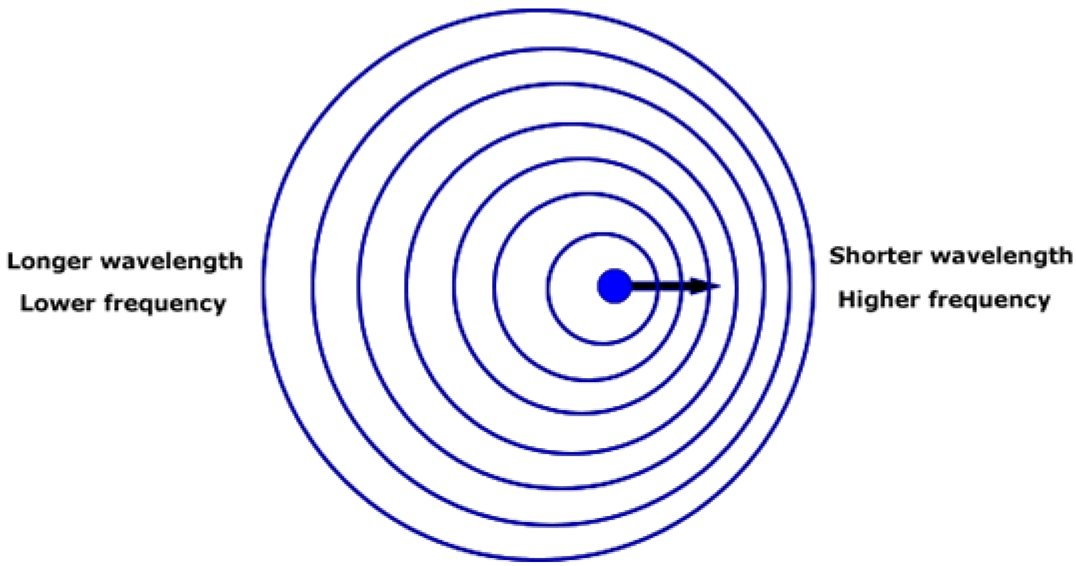


Figure 15: A diagram of the Doppler Effect

designed to remove the unwanted high and low frequencies, and if the transmitter and receiver are moving too fast either towards or away from one another then the frequency of the desired signal could change to the point that it will be filtered out. To compensate for this, the max speed that both the transmitter and the receiver can travel should be noted and compensated for, which will allow the maximum potential bandwidth of frequencies to be able to pass through the circuit. The Doppler Effect can be visualized clearly with the help of Figure 15.

Multipath propagation is a major problem when designing an acoustic underwater system. It occurs when a signal takes multiple paths to the receiver which confuses the system picks because the receiver will pick up the desired signal multiple times. Multipath propagation like many other aspects of underwater communication depends heavily on the where the system is located. In shallow water the effects of the multipath phenomenon drastically increases due to the fact that the ocean floor is closer to the surface of the water, lessening the distance that the

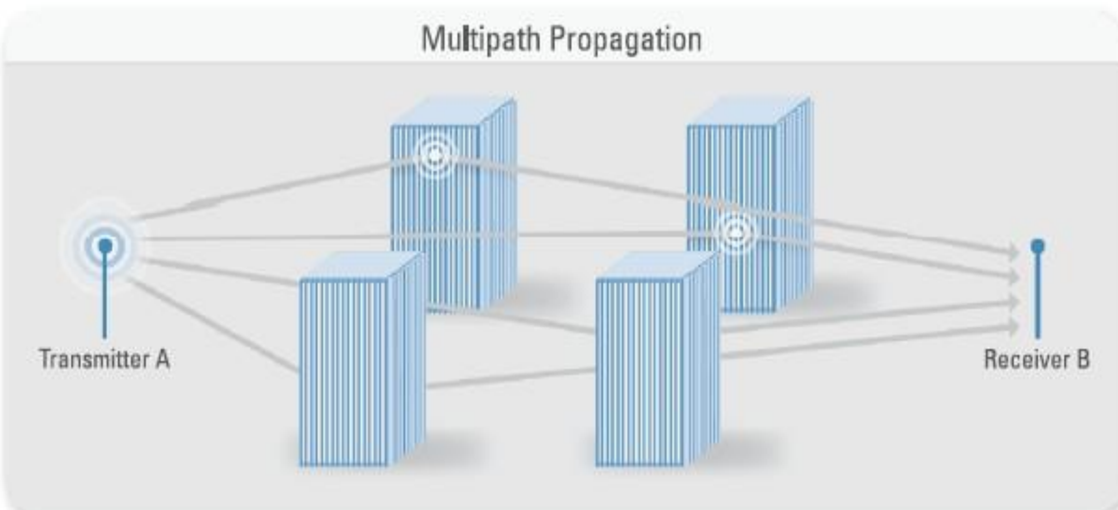


Figure 16: Multipath Propagation

sound waves can travel before they collide with obstacles. While there is no standard definition of shallow water it usually implies the regions of and near the continental shelves, with depth less than about 100 m. An example of a mechanism of multipath formation would be reflection hen the signal reflects off the ocean floor or any other objects in the water (Robert S. H. Istepanian, 2002). An example of multipath propagation can be seen in, Figure 16. This shows how a signal can take multiple path to get to one destination, by reflecting off of different surfaces.

There are two main types of multipath propagation; vertical and horizontal. The aspect that separates these types of multipath propagation can easily be derived from their names; it is the direction that the signals travel. Though the separation may be simple the properties that define then are dramatically different. Vertical multipath propagation has little to no time dispersion, and horizontal multipath propagation can have extremely long multipath spreads that cause time dispersion. These multipath spreads are caused when the signal under goes refraction, reflection, and/or scattering.

Time dispersion is when the multiple pathways spread the signal out in time, so that the length of the received signal is greater than the length of the signal that was sent out. Time dispersion together with multipath propagation causes inter-symbol interference (ISI). This type of interference decreases the reliability of a signal. ISI occurs when the, time dispersed signal that is in the process of being received and the hardware starts to pick up the replica of the signal caused by the multipath propagation. Time dispersion which is caused by multipath propagation is the signal being spread out in the time domain. This can be seen in Figure 17, it shows how that signals that come from an indirect source will start and then end later in time. This can be combated with an initiation sequence at the beginning of the signal, so the system know which section of incoming signals is relevant.

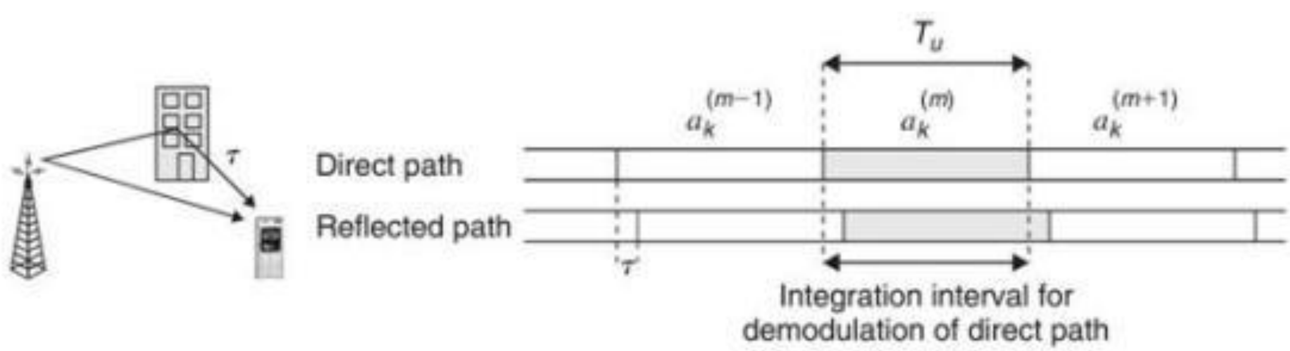


Figure 17: Time Dispersion

This can be seen in Figure 17, it shows how that signals that come from an indirect source will start and then end later in time. This can be combated with an initiation sequence at the beginning of the signal, so the system know which section of incoming signals is relevant.

One of the ways of dealing with the problems present in underwater communications is with spread spectrum methods. Spread spectrum provides a low probability of the signal being picked up by things other than the intended receiver. It reduces the amount of interference that the signal will run into. It would also greatly reduce the affect that multipath and time dispersion will have on the signal. One of two types of spread spectrum can be used; frequency hopping or digital phase modulation. Spread spectrum is the method of running the signal though a circuit that will spread the signal out in the frequency domain, it then can be reversed by running the spread signal through the same circuit to return the signal back to its original waveform.

2.6.2 Electromagnetic Waves

Radio waves which are the section of the electromagnetic spectrum that have wavelengths ranging from hundreds of meters to about one millimeter, they are the most common frequency range used for communication purposes. While they run into many of the same problems that the acoustic waveforms run into their speed greatly reduces the Doppler Effect and multipath propagation.

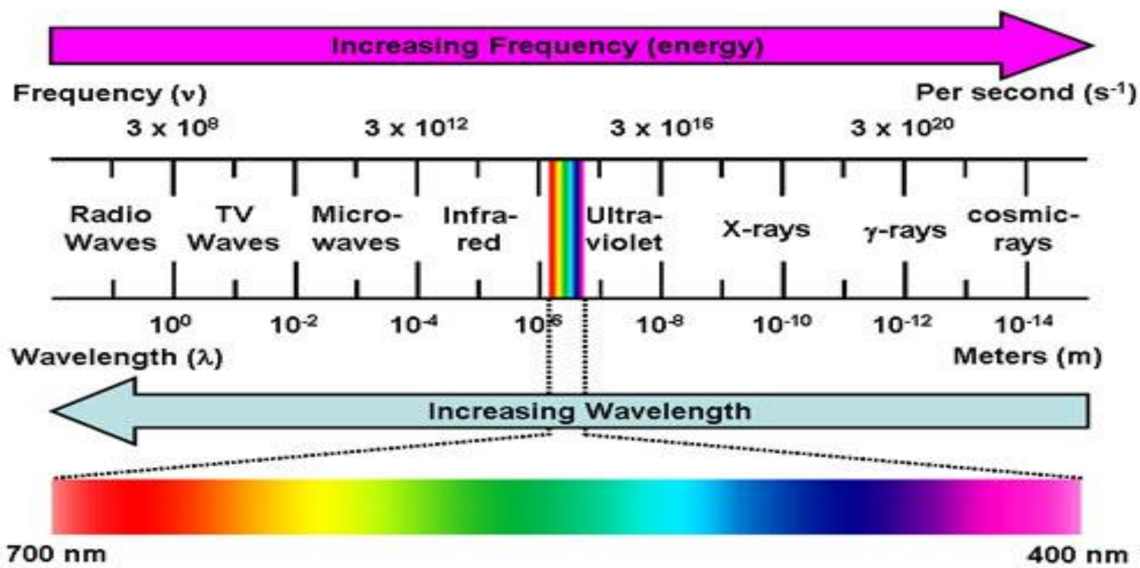


Figure 18: The Electromagnetic Spectrum

Also, because radio waves are part of the electromagnetic spectrum the amount of noise that they are subjected to is immensely less than the amount of noise that a sound wave is subjected to in the ocean. The radio waves carry information by varying a combination of the amplitude, frequency, and phase angle within a certain band of frequencies. The electromagnetic can be seen in its entirety in Figure 18.

One will notice the inverse relationship between frequency and wavelength. Radio waves have the longest wavelength and there for have the smallest frequency. This means that they can travel the furthest, because they use less energy, but cannot carry as much information as waves with higher frequencies.

2.7 Introduction to Electronic Systems

In its most basic form the electronic systems needed to be able to produce an initial signal and send that signal out as an acoustic wave. The system then had to receive that acoustic signal, at random times, transform that acoustic signal into an electrical signal. Then filter out the unwanted electrical frequencies. It then had to sufficiently amplify the electric signal, and transform that amplified electric signal to an electromagnetic wave, that would be sent to the central processing unit. Since the goal of this system was to get the location of people who are in the ocean that start to drown, this system must be able to process all of these signals in real time. Simply put the system only had a very short time to send, receive, filter, amplify, transform, and process the signal to locate a person before they drown.

2.7.1 Signal Filtering

Signal filtering is the process of reading in a sin wave or many sin waves and filtering out unwanted frequencies. There are two basic types of filters; a high pass and a low pass that filter out low frequencies and high frequencies, respectively. These two filter designs can then be combined to create band pass and band reject filters.

$$F_c = \frac{1}{2\pi RC} \qquad (1)$$

The cut off frequency of both the high and low pass filters can be set by using equation (1). Where f_c is the cut off frequency, in hertz, R is the value of the resistor, in ohms, and C is the value of the compositor, in farads. This equation can be used to restrict what frequencies one want to let pass through the filter. As well as restricting the bandwidth of the system.

The main problem that is encountered with filter design is the steepness of the cut off frequency, or the system's ability to keep one frequency while removing the frequency next to it. The steeper the cut off the more the filter oscillates at the cut off. So when designing a filter one has design around the fact that the steeper the cutoff frequency is the more oscillation the system will get when it reaches its cut off frequency.

Figure 19 is the design of a simple high pass filter. They can get more complicated depending on the need that one has for the filter. It filters out the frequencies that are below its cut off frequency.

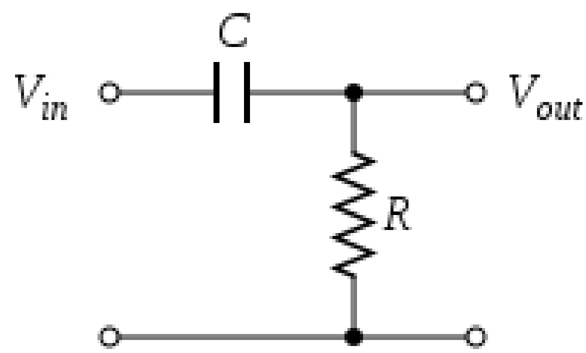


Figure 19: High Pass Filter

Figure 20 is the design of a simple low pass filter. They can get more complicated depending on the need that one has for the filter. It filters out the frequencies that are higher then it's cut off frequency.

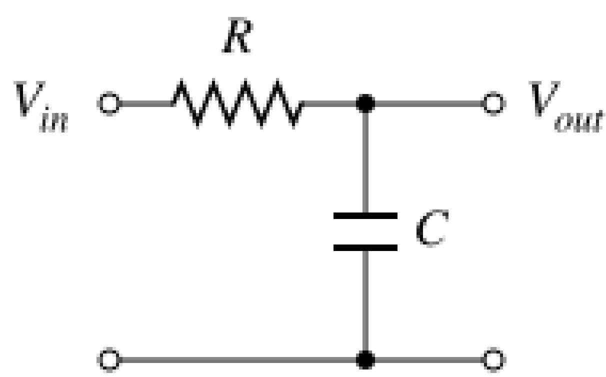


Figure 20: Low Pass filter

A band pass filter is designed when the cut off frequency for the high pass filter is set to a lower frequency then that of the low pass filter. To design a band reject filter one combines a low pass and high pass filter in parallel with each other so that the circuit allows all but one section to pass through unaltered. Filters are a necessary part of any system that does signal processing because they allow the system to take in only the bandwidth that one desires.

2.7.2 Power Amplification

Operational amplifiers or op-amps have may uses but their most common use is as an amplifier. There are two main types of amplifier circuits, inverting and non-inverting. The main difference between the two designs is whether the circuit inverts the signal or not. The op-amp circuit in Figure 21 is a non-inverting circuit that uses the resistor values and Equation (2) to determine the gain of the amp. The type of amplifier used will depend on the functionality of one's circuit.

$$V_{out} = V_{in} * (1 + R_2/R_1) \quad (2)$$

V_{out}, the voltage out of the amp, and V_{in}, the voltage into the amp, are in Volts. R_1 and R_2 are resistor with their values being in ohms.

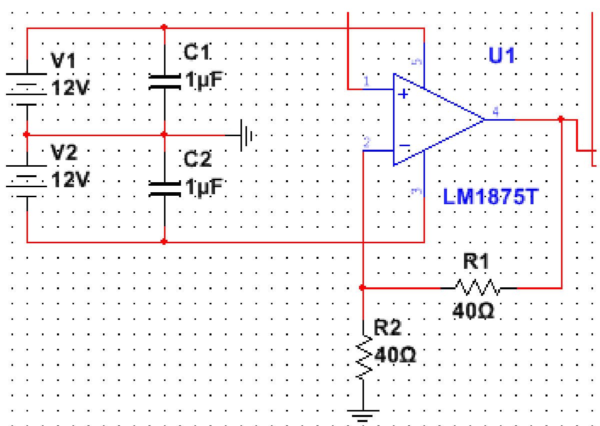


Figure 21: Non-inverting Op-amp

For an amplifying circuit to be fully functional, that is to only amplify the signal, a few different conditions must be met. Firstly the signal must be only amplified this means that no additional sin waves can be added into the circuit. Secondly the signal must be amplified in both the positive and negative direction. This was done in the circuit in Figure 21 where one can see that the batteries, V1 and V2, are put in series with one another and then connected to ports 3 and 5 of the op-amp. This results in the amplification of the signal in both the positive and negative direction. Finally the gain of the op-amp must not be set to high. If this condition is not met then the amplified signal will reach its maximum amplitude too fast and then maintain that voltage. This will result in the plateauing of this signal and will cause the signal to loss its functionality.

CHAPTER 3 – BUDD-E SYSTEM DESIGN AND ANALYSIS

3. Introduction

The final plan devised for the BUDD-E System is a multi-stage process that satisfied the objectives of preventing drowning on beaches and empowering lifeguards to make this possible. The system monitors swimmers' ability to stay afloat by tracking their pulses while they are in the water, and that data is sent to a central processor which checks for signs of danger and triangulates individuals' positions. This data can be provided to lifeguards through a mobile application, utilizing Bluetooth streaming technology to update information in real-time and display it in a straightforward graphical user interface (GUI). Finally, a fast and stable flotation support and water evacuation assistance robot is on standby to rescue swimmers when needed. The robot can be dispatched to a distressed swimmer automatically through the system or manually by a lifeguard. Together, the components of the BUDD-E System serve as an ever-vigilant first responder, designed to detect and respond to support a struggling swimmer within 15 seconds of their inability to consistently support themselves in the water.

After the conceptualization of the full system, the software, custom circuitry, and robot prototype were all designed and implemented simultaneously. While this presented challenges when changes to the design of one subsystem held ramifications for other subsystems, it allowed for a production time much shorter than would have been possible had each subsection been implemented sequentially. A one-third scale model of the robot was designed and built to measure differences between expected and experimental buoyancy, propulsion requirements, and drag forces. Custom proof-of-concept circuitry was developed and built for the wristband and relay buoys. Finally, software was written to simulate a set of up to 15 swimmers using the system at once, and the code was organized so that as physical hardware peripherals were completed, it would not be difficult to substitute the actual input and output signals for the simulated signals.

3.1 System Overview

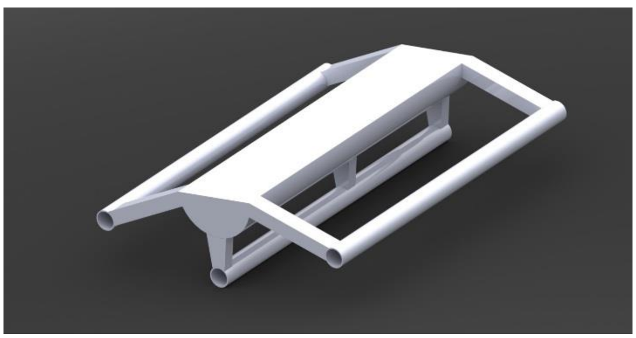
To maintain a real-time understanding of where swimmers are and if they are able to continue swimming safely, the BUDD-E System design utilized a pulse oximeter worn on the wrist. The pulse data is measured and then transmitted acoustically through the water once every five seconds. This signal is picked up by relay buoys distributed along the shore, filtered, and transmitted via radio frequency to the processor on the beach. The signals are processed and triangulated using the intervals of time between transmission and reception. Swimmer positions are converted to GPS coordinates.

Swimmer pulses and GPS coordinates are sent through a Bluetooth connection to a mobile application to be utilized by lifeguards. The application takes the data and overlays icons indicating swimmer locations, the robot position, and lifeguard positions on satellite imagery of the beach being monitored. Each icon is shaped according to the type of entity represented, and swimmers' icons are color-coded to quickly show which are safe, which are in need of immediate rescue, and which require special attention due to potential for problematic situations (for example, moderately elevated heart rates, swimmers approaching the boundaries of the system, or a swimmer who is isolated from other people). The lifeguard is able to look at data pertaining to individual swimmers or view a whole group at once, and she can also instruct the robot to drive to a swimmer if necessary. In warning or emergency situations, the application will use visual and audible cues to alert the lifeguard, and if there is an emergency situation, a prompt to automatically call to 911 will be displayed.

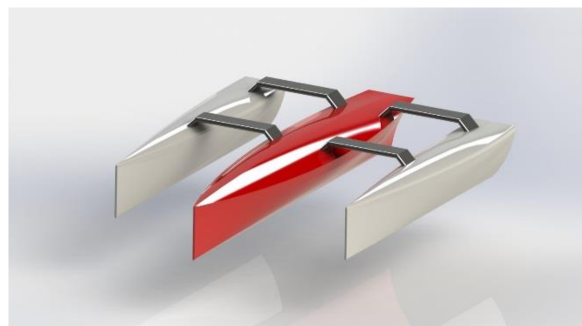
The final component of the BUDD-E System is the robotic support craft. It was designed to stably support and transport one or two individuals through the water in the event of an emergency. The robot is built in the form of a trimaran, maximizing forward speed and roll stability while minimizing drag from wetted surface area. This design met the necessary characteristics for the robot to operate within the parameters for reaching distressed swimmers as quickly as possible, while maintaining a form factor that would provide steady support amongst waves and with uneven passenger weight.

3.2 Designing the Hull

Designing the hull had several challenges that had to be overcome. Speed and stability requirements were needed and also ease of construction and assembly of the BUDD-E System. Several iterations of the design were considered before the final version was selected based upon the intended objectives of the BUDD-E System. The first design (Figure 22A) was to use PVC pipes attached to a main body. The center bottom pipe would contain a rim-driven motor. The goal of this design was strong simplicity of the build essentially entailing a couple of pipes being bolted together with electronics thrown in. This design was scrapped due to the shear lack of hydro dynamics which would severely affect the speed of the craft which was one of the main design points. Also, rim-driven motors were more expensive than planned for and defeated the purpose of the ultra-low budget design.



A. Trimaran Design 1



B. Trimaran Design v2

Figure 22 - First two trimaran designs

Version two was a jump in design that allowed for the first fluid velocity test in Solidworks. This version formed the basis for the final version and was designed off of a modified john boat design for each of the three hulls. As seen in Figure 22B, the design made drastic gains in sleekness while keeping the same stability that a trimaran should have. Because this design seemed much more realistic than the previous one, it was decided a flow analysis

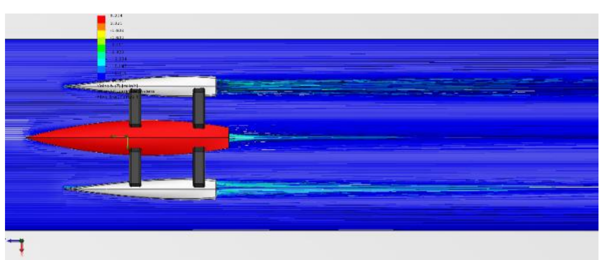


Figure 23 - Fluid velocity analysis at 20 mph

would be a good next step to understand what kind of forces would be involved in pushing water aside. Figure 23 shows a flow analysis performed at 20 mph on the Solidworks model. It is evident that the outriggers were creating a greater velocity reduction in the surrounding water and needed to be redesigned to remedy this.

The two main reasons many ships have flat sterns are either placement for a rudder (in sailboats) or a mounting platform for an outboard engine (motor boats). In the case of a trimaran of this design, there was no need for rudders on the outriggers, nor mount points for powered movement since stability was the outriggers primary concern. As such, the outriggers were redesigned such that the sterns came to points similar to the bows. This small design change reduced the turbulence behind the craft which in turn reduced the necessary force required to travel through the water at the desired speed of 20 miles per hour.

However, with the choice of a jet drive as the propulsion system for safety reasons, a boxy, internal compartment needed to be added to the center hull to allow for the drive line components to fit. To design this box the components needed to be ordered, but the force the parts delivered was based on the hydrodynamic efficiency of the hull. So before any changes were made, the drive line was ordered based on the flow analysis. Solidworks outputted 40N of force required to obtain the desired speed and so components that could push a small amount past this were ordered to allow the final design to finish.

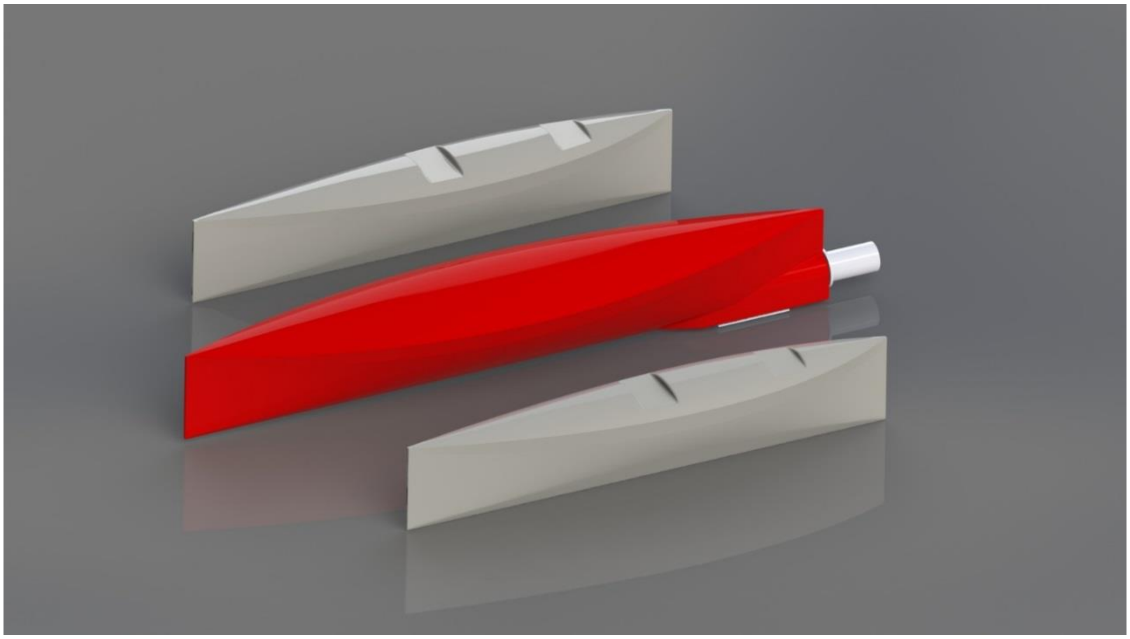
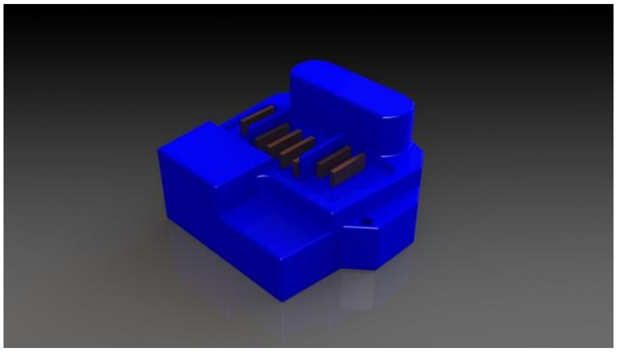


Figure 24 - Trimaran v2.5

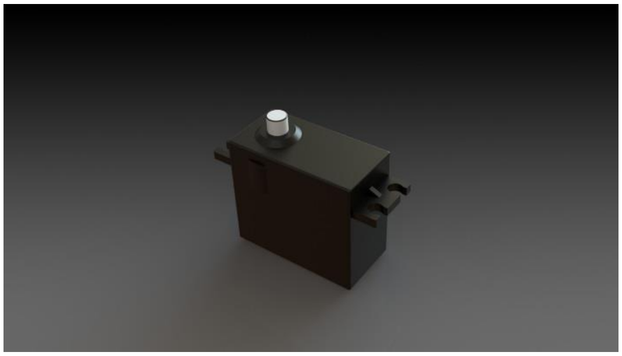
As seen in Version 2.5 of the design (Figure 24), the outriggers have had their sterns brought to a point to increase their hydrodynamic efficiency. Also of note was a very rough model of the jet drive and a suitable compartment were modeled from dimensions provided by the manufacturer. The challenge with this was the dimensions that were given only applied to a hobbyist enthusiast who had their hull already made.

Another design aspect that was considered at this point was the method by which the outriggers attached to the center hull. Two plates per outrigger, each with two tapped ¼-20 holes were designed to be implanted into the outriggers allowing for a variety of attachment methods.

A. Jet Drive



B. Electronic Speed Controller



C. Servo

Figure 25 - Photorealist render of driveline components

The expected interface at this point was a simple metal cross beams that ran the full width of the craft to hold everything together. At this point the center hull was still technically a completely solid model and had no room for components. Once the drive line parts were in hand they were modeled in Solidworks (Figure 25) and the design of the internals could be started.

To fit these components, a long cavity was opened up the length of the craft as well as hollowing out the rear compartment. The hull had many minor revisions as the driveline assembly made minor changes but the order of components stayed roughly the same. The batteries were placed in the long cavity so they could be adjusted to center the buoyancy, while the speed controller went under a hatch that had yet to be created while the moving components were all assembled on a plate that would be the bottom of the rear compartment. This was all done in tandem with the design of the driveline assembly to assure fit. At this point two main things were left to design: the exact method by which the outriggers would be attached to the center hull and how the operator would access the internals to turn on/off the electronics as well as perform repairs.

The access hatch was designed to minimize use of CNC mills and so acrylic was used since it is easy to laser cut. The main unfortunate property of acrylic for our purposes is that it is brittle and doesn't not hold tapped threads well. Because of this a threaded insert assembly was developed with four total plates. The bottom three plates acted as a ring around the lip of the hatch and the center of these held 14 evenly spaced ¼-20 nuts. The nuts vertical motion was stopped by the top and bottom sandwich plates while it's lateral and rotational motion was stopped by the hexagonal cavities cut into the middle sandwich plate. These three plates were designed to be fused together then be permanently attached into the hull. To keep out water, the top sandwich plate had a rubber gasket in a ring both inside and outside the 14 holes. Finally the top plate was held down with (14) ¼-20 socket head cap screws allowing for even distribution.

Unlike the hatch design, the outrigger attachment method took a little more time and many design revisions. The original design (Figure 27) called for flat metal bars to run the full width of the craft to hold the three hulls together. In this part of the design the main challenge

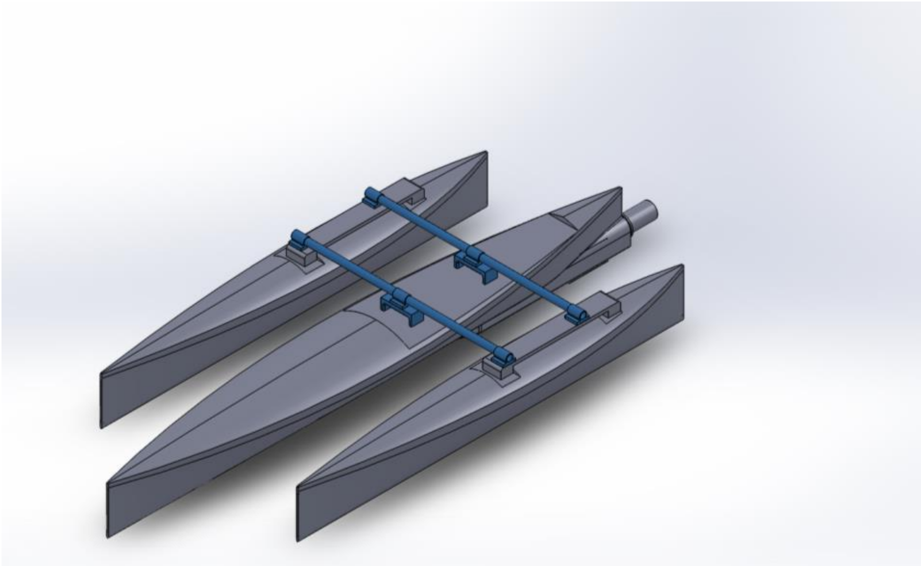


Figure 27 - Basic crossbeam concept that require detachment of parts to access the hatch

was to create a system that didn't interfere with access to the outriggers. The first several designs required disassembly for the hatch to be opened which is incredibly inefficient.

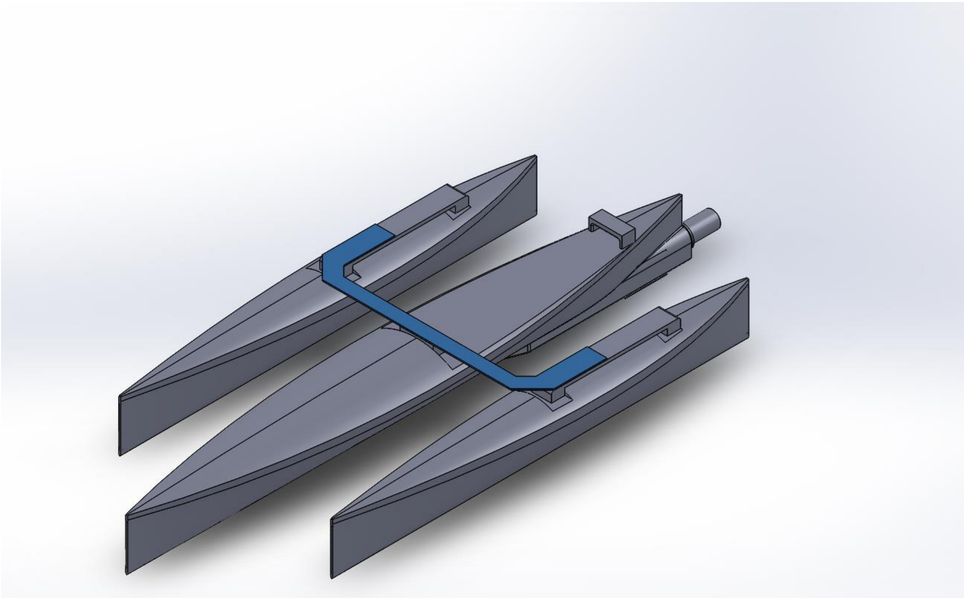


Figure 26 - Design to increase access to hatch

Even for a prototype, disassembling the craft just to access the hatch was not okay so the back beam was removed and the front beam was moved forward as seen in Figure 26.

This design increases access to the hatch but lacked in structural integrity. Large moment would act on the beam without a second beam to create a counter-moment. The solution to this was to make the beam a full D-shaped loop which can be seen in Figure 28.

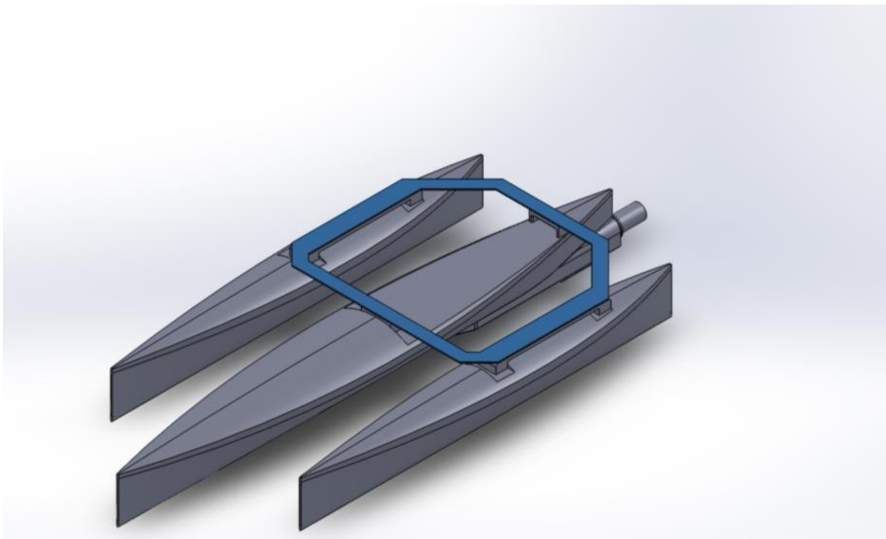


Figure 28 - Full D-shaped ring for mounting the outriggers

This design greatly increased access to the hatch, however, the hatch's length would need to be decreased to allow for the mount points and this would in turn greatly restrict our access to the internal components. These series of designs were all based around the basic cross-bar idea and while each idea had improved on the previous one, none of them truly felt right with the overall flow. The group went back to the drawing board and came up with an elegant solution that fit perfectly. This solution was to make the center hull a winged uni-body design where the

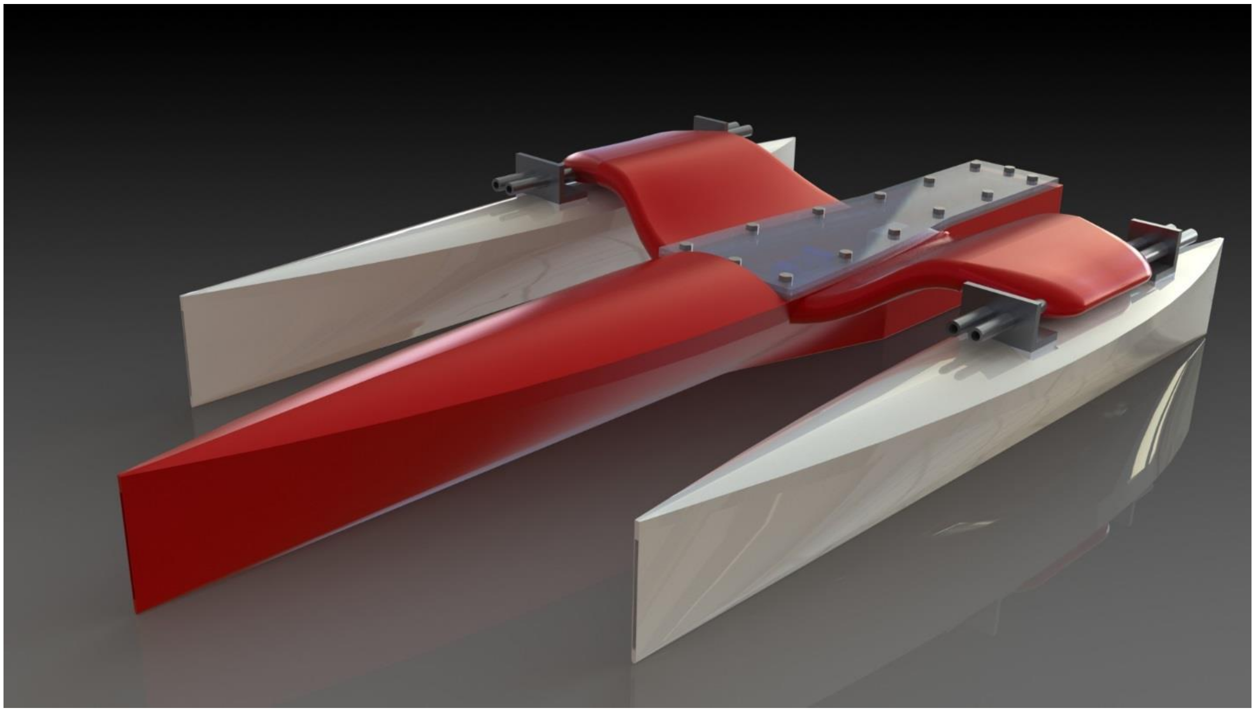


Figure 29 - The final design for the BUDD-E trimaran

wings, which would be part of the hull, would reach out to the outriggers and attach there. This design had numerous advantages: decrease complexity of attachment system and move it to the outriggers and away from the center hull and leave the hatch completely exposed.

Figure 29 above shows the wings and their attachments to the outriggers. Due to unknown density of driveline components and uncertainty in the actual creation method, the out riggers attachment system has adjustment to control the center of buoyancy as a paramount design feature. Two ½ inch pipes were attached to each wing of the center while two brackets are attached to each outrigger. Having two pipes stops the outrigger from rotation about the pipe's axis while still allowing for the outrigger to slide forward and backwards to trim the buoyancy. Once the proper position has been obtained, pins can be installed to stop all motion.

3.3 Creating the Hull

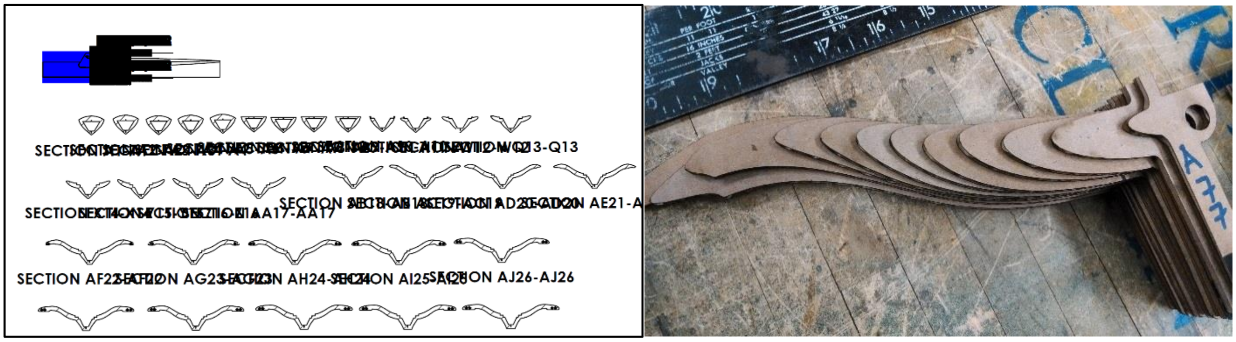
Creating the triple hull for our project proved to be a more immediate challenge than we expected. The design, as seen above, ended up with several complex curves that did not lend themselves well to most boat building techniques. To create our design out of wood would have taken more time than we had available especially when the group had no boat building experience. Most fiberglass or carbon fiber boats are made with female forms that allow the builder to lay the material in and reuse the mold for several boats before needing to repair or replace it. A leading challenge was to create a novel boat building technique that worked well for prototypes.

The design goals identified for this novel technique were: low cost, ease of workmanship/high material forgiveness, and the ability to work with complex curves. Creating the form out of foam was suggested but unfortunately CNC Mill capable foam was too expensive and no group members had the ability to hand carve foam. Several other ideas were scrapped due to our inability to execute them. The lead up to the final idea was the concept of laser cutting ribs out of wood then stretching fiberglass across them. This idea was discarded due to our inability to achieve smooth curves between the ribs. Finally a way to meet all of the building technique goals was discovered. The craft would be laser cut cross sections made from cardboard. Cardboard is fairly strong in compression on its axis considering the cost of material and the laser cutting process would allow for the most complex curves to be made incredibly simply. It is also light enough that a solid block the size of the craft would not be an issue. Obviously, cardboard is not waterproof so a shell of fiberglass would be added to give the craft waterproofness as well as structural rigidity.

3.3.1 Drawings and Laser cutting

To go from 3D model in Solidworks to laser cut cardboard was a fairly straightforward but time intensive task. The thickness of each cross section was to be the thickness of the average piece of cardboard which we measured at 0.16 inches. This was divided across the length of each hull and it was found that 196 cuts were necessary for each outrigger while 260 were necessary for the center hull. To reduce time to make these cuts, a simple macro was written in Solidworks to create these planes.

Once the planes were created, a drawing was made for each unique hull (Figure 30A). Then cross section drawings were manually created at each one of these planes and compiled into a comprehensive sheet that could be printed with a little more work. From Solidworks the



A. Cross sections for laser cutting

B. Cardboard cross sections

Figure 30 – Cross sections in digital form (A) and physical form (B).

drawing was exported as a DXF and then imported to Autodesk Inventor on the computer attached to the Versa 4.6L 60W laser cutter. The DXF file was then cleaned for extraneous drawing lines and sent several sections at a time to the cutter (Figure 30B).

3.3.2 Preparation for Fiberglass

To prepare for the fiberglass coating process, the loose cross sections had to be assembled in proper order and then held together. To keep the cross sections adjacent to each

Figure 31 - The outrigger cross sections mid-assembly

other, a 3in center "beam" of cardboard was strung through the center of each piece of cardboard. This held each cross section in alignment within its respective plane.

This assembly technique can be seen in Figure 31 above. At this point in the process, the hull has taken on its shape but wiggles like a fish, which is not very useful when trying for a straight keel. To resolve this issue, each hull has a layer of painters tape applied. The light adhesive on the tape allowed for re-laying strips that may have over tightened in a section. An

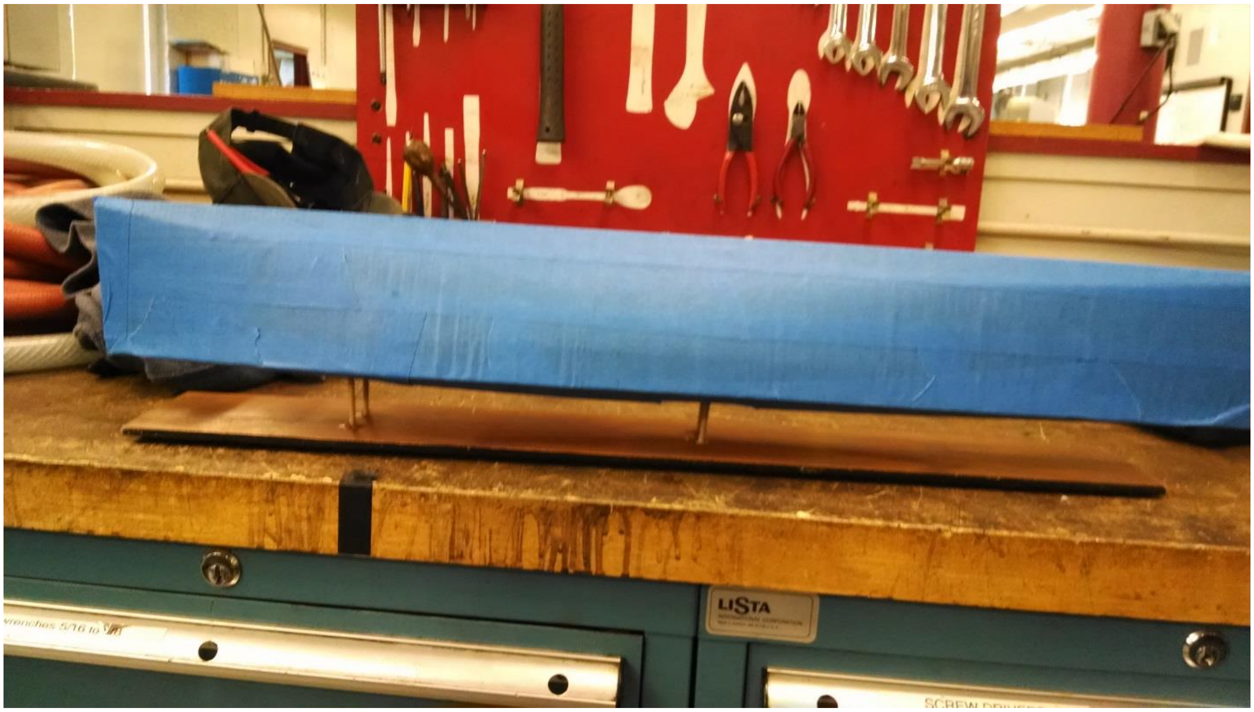


Figure 32 - Outrigger prepared for the fiber glass process.

outrigger completely prepared for the fiberglass process can be seen below in Figure 32.

To meet alignment tolerances, it was found that using an angle beam along the keel while taping helped keep the entire system centered. Once taped, the hull was placed keel up on a stand to begin the first coat of fiberglass.

3.3.3 Fiberglass Application and the Associated Learning Process

The fiberglass application process itself was a learning curve for the group. The two outriggers were done before the center hull and acted as test subjects. Almost every layer was done in a different method than the previous one as the group learned technique by trial and error. At first, strips were applied running the length of the hull, similar to wooden planks (Figure 33).

When strips were used, fraying became an issue. As the resin was applied, it would start to pull off threads from the edge of the fabric and those threads would harden into narrow bumps.

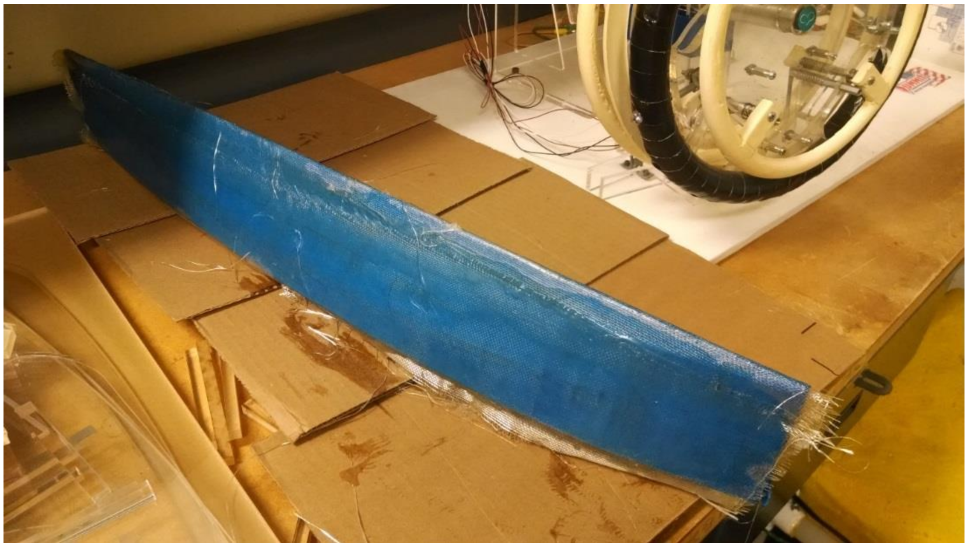


Figure 33 - First layer of fiberglass on the first outrigger.

These were difficult to sand due to surrounding fiberglass that didn't need sanding receiving it anyways. A close up of sanded threads can be seen in Figure 34.

Figure 34 - Close up of sanded fiberglass threads.

To stop the fraying issue the edge of the fiberglass was taped off. This also had the positive side effect of providing a very clean and straight line at the edge. The lack of straight edge effects (also seen in Figure 34) the evenness of sanding which in turn causes waves in the hull. The taped edge while being the next level of technique still fell flat since it didn't allow for stretching the fiberglass to remove bubbles and it didn't take care of the nasty edge between strips. To combat this a new technique was developed. As seen in Figure 35, two metal bars held fiberglass stretched over the hull in place.

Figure 35 - Fiberglass stretched over hull and clamped in place.

The fiberglass when preformed to the hull allowed for plenty of alignment revisions before the resin was applied. Previously, it was a frantic race to place the cloth down, resin it and then align it before the resin began to cure. While this gave us the cleanest application process the one downside was that there was no opportunity to place resin underneath the fabric which meant that a smaller amount of hardener had to be used in the resin to give it time to absorb. This in turn increased our cure times and slowed the process.

The double bar technique worked well for when the keel was up since the hull easily rested on the relatively flat top surface. However, for applying fiberglass to the top, a different technique was needed. The concept of pre-stretching was combined with the previous taping process which is demonstrated in Figure 36.

While adjustment did require lifting tape to remove bubbles and creases, the end result was almost identical to the double bar technique. Due to the reduced hardener in the resin, the cure times increased and one layer actually contained so little hardener that it never fully cured. This introduced another alteration to our process. In between layers of fiberglass was a coat of

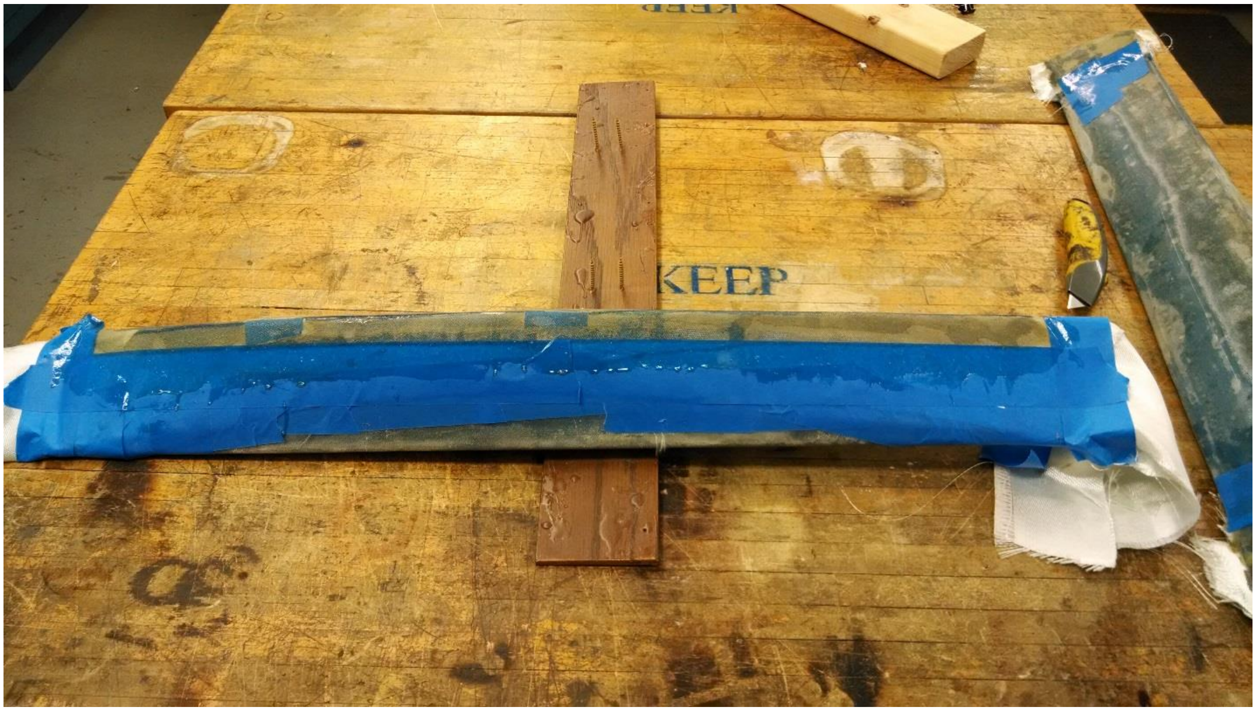


Figure 36 - Alternate pre-stretched fiberglass technique.

just resin. This resin could be mixed with a large quantity of hardener and act as a "reset" layer which helped clean up inconsistencies in the previous layer. The pure resin layer also allowed for the sanding out of high and low points without worrying about compromising a layer of fiberglass.

To allow for the attachment of the outriggers, metal interface plates were imbedded in the outrigger hulls. To do this, a strip of fiberglass and resin was applied to the top of the outriggers and while this was still wet the plates were pressed into place.

To achieve a strong adherence the plates were sanded first then several layers of fiberglass were applied over it. The edges of the plates had square corners which unfortunately meant that the fiberglass, when pulled taut, created a tent-like shape. The plates were attached on

A. Fitting and planning fiberglass housing B. Embedded Plates

Figure 37 – Fiberglass process to embed mount plates

their top and bottom surfaces and were located in pockets within the cardboard that prevented sliding along the hull’s length, but the tenting left possibility for lateral movement. To fix this, resin was injected to fill the tent using a basting needle (Figure 38).

Figure 38 - Basting needle injecting epoxy resin into gap between fiberglass, plate, and hull

Injecting the resin to fill the gap around the plate worked better than expected. Four injections were expected per plate, one on each side. Instead, as the resin flowed in, it traveled around all four sides. Once the resin had set, the damage from the injection site was sanded away and the result was solid. Once all of the coats of fiberglass had been applied, each individual hull was waterproof and structurally sound. However, the fiberglass was not particularly smooth and needed some waves taken out of it as well as beautified before it could make a proper watercraft.

3.3.4 Finishing the Hulls

The outriggers with their simpler curves lent themselves to more even layers of fiberglass and because of this needed less finishing work than the center hull. The center hull had its issue concentrated around the wings which required fiberglass to curve around the non-linear leading

Figure 39 - Left: Center hull with Bondo caked on wings before sanding and sanded Bondo on bow. Right: Last layer of Bondo on one outrigger (no sanding).

and trailing edges which caused wrinkles and bubbles. The damage was mitigated with serious sanding but the real solution lay in Bondo, an automobile dent filler. Layers of Bondo were applied to the main hull and sanded down until the high spots of the fiberglass showed through. This smoothed out every blemish with the unfortunate side effect of adding bulk (Figure 39).

Figure 40 - Center hull with a fresh coat of paint

Once the hulls were formed, waves removed, and cracks filled it was time to paint. Every hull got 5 layers of paint applied in 20 minute intervals followed by 3 layers of clear coat 15 minutes apart. A picture was taken in the middle of the process and can be seen below in Figure 40.

All painting was done with spray paint and when all coats had been applied each hull was given 24 hours to cure before it was handled. Once painting had finished the hulls were marked complete. It had been a brutal process taking hundreds of man hours and fraught with challenges that had to be overcome, but the result was a thing of beauty that the group could be proud to call their own.

3.4 Selection of Driveline Components

Choosing the components of the driveline for our robot was a very important process, as the choices we made determined how well it would work and how close to our design goals we could get within our budget. The flow simulation that was performed on the hull in SolidWorks provided a necessary thrust to propel the robot to 20mph. From these calculations, we determined what propulsion system we needed. Having determined the propulsion system, we were then able to choose the correct motor to power it. After selecting the motor, we were then able to choose the motor controller and batteries to match its required input voltage and amp draw.

3.4.1 Method of Propulsion

The initial choice to be made was between exposed or shielded propulsion systems. As safety is among our primary concerns for this vessel, we opted for a jet drive instead of an exposed propeller. An exposed propeller can quickly do a large amount of damage to anyone who gets to close. A jet drive's moving parts are contained within it, greatly limiting the potential for it to cause harm to someone being rescued. There are a number of jet drives available in the scale we needed. Table 1 shows the jet drives, their cost, and any manufacturer provided statistics that could be found.

Table 3 - Jet Drive Comparison

Make Model	Static Thrust [Newtons]	RPM Range	Power Input [Watts]	Material	Impeller Diameter [mm]	Cost (Converted to USD)
Graupner Model 5	Unlisted	Unlisted	Unlisted	Aluminum/ ABS Plastic	78	~$275.00
MHZ Jet 52	120-240	16,000	2,200	Machined Aluminum	52	~$410.00
MHZ Jet 64	400	16,000	9,000	Machined Aluminum	64	~$755.00
MHZ Jet 80	500	12,000-14,000	15,000	Machined Aluminum	79	~$1060.00
HobbyKing Jet Boat Drive	Unlisted	Unlisted	Unlisted	Machined Aluminum	53	$403.57
Kehrer Modelbau Jet 28	25-40	13,000-16,000	200 - 400	ABS Plastic	28	~$70.00

The Graupner "Jet 5" in Figure 41, while popular in the model jet boat world, does not have nearly enough information available to be appropriately considered for our robot. By comparing impeller size we can presume that its thrust range is similar to the MHZ Jet 80, which has a thrust range far in excess of our needs.

Figure 41 - Graupner Model 5 (WorthPoint)

MHZ has three jet drives available, the Jet 52, the Jet 64, and the Jet 80, shown in Figure 42A/B/ C respectively. These jets are precision machined from aluminum and have a reputation

A. Jet 52 (MHZ)

B. Jet 64 (MHZ)

C. Jet 80 (MHZ)

Figure 42 - MHZ Jets 52, 64, 80

for high quality. They also provide massive amounts of thrust, ranging from 120N up to 500N for the Jet 80. This quality and power comes with detractors though, as they are also very expensive. Given their high prices and thrust outputs many times higher than necessary, they were not considered for the robot beyond the initial research stage.

The HobbyKing “Jet Boat Drive” appears to be an unpainted copy of the MHZ Jet 52, listed as having a nearly identical impeller diameter. It has a reputation for slightly suspect construction, perhaps due to being a copy of the MHZ. When comparing the MHZ Jet 52 in

Figure 44 - HobbyKing Jet Drive (HobbyKing)

Figure 42A with the HobbyKing Jet in Figure 44, the similarities are very obvious. Before even considering the high probability of additional work being required to fix manufacturing issues, the price of the HobbyKing Jet drive puts it well outside the budget of this project.

Figure 43 - Kehrer Modelbau Jet 28 (Kehrer Modelbau)

The Kehrer Modelbau Jet 28 (Figure 6) meets the 40N of thrust required by our flow simulations and is less expensive compared to other options. It was available form a seller in the US, limiting the amount of time and money spent on shipping. In the end, we selected the Kehrer Modelbau Jet 28 along with a KaMeWa style steering and reverse attachment, as show in Figure 43.

3.4.2 Electric Motor selection

Based on the required input of out jet drive, we were able to determine the requirements for our electric motor, which would be powering it. The initial choice was to go with a brushed or brushless set up. Brushless motors are much more powerful, but much more expensive. Brushed motors are not as strong as brushless, but tend to be much cheaper and less susceptible to damage. In addition to the initial cost of the motor, brushless motors require more expensive controllers. This added cost was enough to push in favor of a brushed motor for our prototype.

There were three different brushed motors considered to power the jet drive. One is sold by the same company that makes the jet drive, the KMB 700 BB, pictured in Figure 45 below. In

Figure 45 - KMB Motor (Modelbau)

the model name, KMB is the company, 700 refers to the size class of the motor, and BB means that it has ball bearings instead of cheaper metal bushings supporting the axle. It is a 12v motor, and can safely be run up to 19.2V, at which its no-load max speed is 17,190 rpm (Modelbau). This motor would have been ideal; as it is the motor the jet drive is designed to mate with. Unfortunately, the US distributor did not have any in stock, and it was deemed that shipping one from German would take too long and be too expensive.

The next choice was to buy a Johnson Motor 700 Class motor. These are nearly identical to the KMB motor, likely being the factory supplier for KMB. The motor is the same size, has the same voltage ratings and the same mounting-hole spacing, missing only the KMB label on the heatsink. However, they were out of stock at every supplier that carried them.

The third option was what was installed into the robot, a Dewalt 18v motor, shown in Figure 46. These are sold as replacements for the Dewalt Hammer Drill. This motor is larger than the other choices, being 13mm longer and 3mm wider than the KMB motor. Its maximum

Figure 46 - Dewalt 18v Motor (Powertool Vault)

RPM far exceeds the requirements of the jet drive, turning at roughly 1125 RPM/volt (Robot Marketplace). This allows us to run the motor within its manufacturer specified voltage range, increasing its lifespan and lowering our power requirements. It required some modification to work, as the pinion gear (seen in the above figure) was press fit on at the factory and the jet drive needed a straight shaft. Thus, the gear was cut off and a flat spot was made on the motor shaft. Using this motor also required the machining of a new mounting plate, as the mounting holes on this motor are farther apart than those of the jet drive.

3.4.3 Motor Controller Selection

Having selected a motor and jet drive, the next step in designing the driveline of the robot was to choose a motor controller. To reach the desired output from the jet drive (40N), an input of 16,000 RPM or greater is needed. The jet drive also has a manufacturer specified max rpm of 20,000 RPM, beyond which either the impeller cavitates or the stresses are too much for the parts. Wanting to leave a safe buffer on this limit, a calculated max of 19,000 RPM was determined. The motor under no load reaches this limit at ~17 Volts. An advantage of the scale of our prototype was that we could use hobby-grade radio control car and boat parts. In the hobby, motor controllers are referred to as electronic speed controls or ESCs.

We initially considered using the same motor controllers as the previous MQP, the "ProBoat Waterproof ESC with Reverse" (shown in Figure 48). The three from before were all

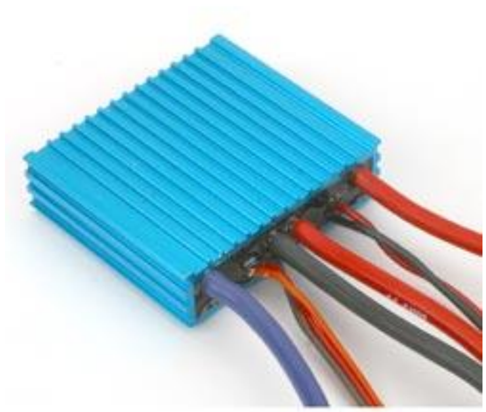


Figure 48 - ProBoat ESC (Proboat)

destroyed after having too much current drawn through them, so we would have to buy new ones. Upon investigating the controllers, it was found that this would have required a smaller motor and input voltage than ideal

Figure 47 - Traxxas EVX-2 ESC (Traxxas)

The second option considered was the Traxxas EVX-2. This ESC is waterproof, easily adaptable for water-cooling, and has a reputation for durability that comes from its heavy use in radio controlled cars and boats. It is shown in Figure 47. It is not the cheapest option, but includes the Low Voltage Cutoff (LVC) necessary for the use of Lithium based batteries. This opened up the selection of batteries, as a separate LVC would not need to be purchased, unlike other, cheaper ESC's. The EVX-2 has a max voltage of 16.8V, which, when powering the motor, would produce 18,900 RPM. This is ideal to maintain the safe buffer from the jet drive's max RPM.

3.4.4 Battery Selection

In selecting batteries for the prototype, three main types were considered. These were Lithium-Polymer (Li-Po), Lithium Iron Phosphate ($LiFePO_4$), and Nickel-MetalHydride (Ni-MH). Table 4 below lists all available comparable specifications for the proposed batteries.

Table 4 - Battery Comparison

Battery Type	Li-Po (HobbyKing)	$LiFePO_4$ (HobbyKing)	Ni-MH (All-Battery)
Brand	Turnigy	Turnigy	Tenergy
Configuration	2S1P	2S2P	7S
Cell Voltage [V]	3.7V	3.33V	1.5V
Pack Voltage [V]	7.4V	6.66V	8.4V
Combined Voltage [V]	14.8V	13.32V	16.8V
Capacity [mAh]	5000mAh	4500mAh	3800mAh
Constant Discharge [A]	100A	135A	38A
Weight of Pack [g]	282g	317g	456.4g
Cost (2 Packs)	$33.02	$51.12	$55.99
Cost (equipment)	$30.00	$30.00	Free
Cost Total (-S&H)	$63.02	$81.12	$55.99

Lithium Polymer batteries are the popular choice for more high-power radio control vehicles, as they offer very high runtime for their weight. They do require some special equipment, however, as multi cell packs must be carefully balanced when charging and discharging to prevent fires. Individual cells have a voltage of 3.7V, meaning that a pair of 2S (2 in series) packs, as shown Figure 49 would produce 14.8V and 16,650 RPM. This means that, while not using all of the voltage that the ESC can handle, this battery set-up would provide enough power for the specified thrust of 40 Newtons. Their high price, because of the required equipment, eliminated them as an option for this project.

Figure 49 - Turnigy 5000 mAh Lipo battery (HobbyKing)

$LiFePO_4$ batteries offer significant advantages over LiPo. They are chemically much more stable, greatly reducing the chance of a fire. They still require a balancing equipment for charging and use, but are much more resilient being improperly handled. They can also be

Figure 50 - Turnigy 4500 mAh LiFePO4 battery (HobbyKing)

charged very quickly, reducing down time when multiple packs aren't available. They have cell voltage of 3.33V, meaning a pair of 2S packs would again be used, as 3S would push the voltage too high for the ESC. A single 2S pack is shown in Figure 50 above. The 13.32V from these packs would provide 14,985 RPM from the motor. This would not be enough to achieve the desired thrust, disallowing them as a choice for the robot.

Ni-MH batteries are the cheapest of the three, and also the weakest. They have an individual cell voltage of 1.5V, less than half that of the other two. They also weigh much more for equal capacities, making the whole system less efficient. They can be charged on the most basic of chargers, and one team member had one that could be used, further reducing their cost. Due to their low voltage, however, a total input voltage of 16.8V can be reached through a pair

Figure 51 - 2x Tenergy 7S NiMH packs (All-Battery)

of 7S 8.4V packs. The packs specified for that set up are shown in Figure 51. This completely uses the ESC's available range, and pushes the motor to a maximum of 18,900RPM. At this speed, the jet drive would discharge more than 40N of thrust, propelling the robot to speeds over 20MPH. As this extra speed would allow us to make accommodations for how the boat was built and absorb some losses due to human error, as well as being the cheapest option by a large margin, Ni-MH cells were chosen for the project.

3.5 Building the Driveline

Having purchased all of the parts of the driveline and completed the construction of the hull, the final step was to assemble the driveline and mate it with the hull. The entire stern end of the boat was designed to allow preassembly and testing outside of the hull. After finalizing the orientation and placement of the driveline, the whole assembly would then be inserted as one piece and epoxied into place for a watertight seal.

Throughout the construction of the prototype, a concerted effort was made to avoid complicated milling procedures whenever possible. As such, the only metal parts that required machining were a motor mount plate and a collet. Both of these parts were designed to accommodate the use of the DeWalt motor. This motor was bigger than the motor the jet drive

Figure 52 - Machining Motor Adapter Plate (Cheston)

was originally designed to work with, which caused two major issues. Firstly, the mounting holes on the motor were farther apart than the mounting holes on the jet drive. To make this combo work, we drilled and tapped a motor plate with two separate sets of holes. One set was exactly the same size and spacing as the jet drive, the other set, slightly offset, was drilled for the motors mounting holes. To accurately place the holes without using a mill, an acrylic template was Lasercut from the Solidworks drawing. This plate and the template can be seen in Figure 52, having just been on the drill press.

The second major obstacle presented by the use of the DeWalt motor was the size difference between the motor's output shaft and the jet drive input shaft. The motor shaft is 5mm and the jet drive's input is 3.5mm. For this we created an aluminum collet, with a 5mm hole on one side and a 3.5mm hole on the other. We then drilled and tapped holes for setscrews, to lock

Figure 53 - Jet Drive Modified for Setscrew Access (Cheston)

the shafts into the collet. This collet fit exactly as planned, but did require some modification of the jet drive to enable easier access to the setscrews. This modification involved the removal of the top shield of plastic above the collet. The finished product is detailed in Figure 53.

Once all assembly components had been machined, the driveline could be assembled. The jet drive was adhered into place. Then the back plate was glued with an L-bracket to give the butt joint structural integrity. Once this cured the motor plate and motor were attached, the servos were prepared and their support structure was glue to the base plate.

3.6 Assembling the Trimaran

Assembling the components of the trimaran was a fairly straight forward process. L-Beam brackets were machined from 2"x2" aluminum stock and used to attach the mounting plates on the outriggers to the guide bars on the wings of the center hull. Because the alignment of the mounting plate holes had been done by hand there was some difficulty in aligning the matching ¼-20 holes in the brackets. Once this was figured out, all that remained was to insert the driveline and hatch. Due to their inherent designs, both the driveline and hatch took little effort to assemble. The driveline simply slid into place along the length of the rear compartment until the stern plate made contact with the pocket it rested in. The hatch on the top of the boat simply dropped into place. Both of these components were adhered into place with 2-part quick dry epoxy. At this point the trimaran just needed its batteries and control system which were dropped into place and wired in. The last finishing touch was simple cable management and then bolt down the top of the hatch.

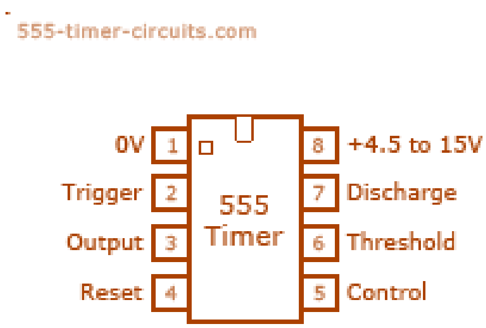
3.7 Buoy/Wristband Electronics

The wireless localization system designed was required to fulfill the obligations of two distinct categories. The first category was the ability to transfer acoustic sound waves into radio waves. This requirement was established because only compression waves, like sound waves, have the ability to travel through the water. Combing the previously requirement with the infeasibility of using sound waves to travel from underwater to above water, due to refraction of waves as they pass to a different medium causing the signal to be unreliable to use for localization, the second obligation was established. The second requirement dictates the system must be able to process signals and determine identify the origin of the signals in real time. Location of a drowning victim must be conducted immediately in real time because the window of time for the robot to reach the victim is limited, based on rescue to survival rates. This fact also supported the use of transforming the signal from an acoustics wave to an electromagnetic wave, because electromagnetic waves travel exponentially faster the sound waves. The use of electromagnetic waves would cut down on the amount of time that it took for the signal to reach the central processor on the beach. While this might not seem like a lot of time it could be life or death for a person that is drowning.

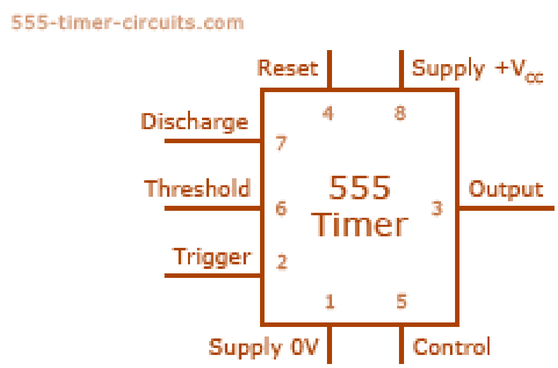
The system was designed to use hydrophones that picked up acoustic waves which would then be transformed twice, the first time into electric signals, and the second time into electromagnetic waves. The signal would ultimately be sent to the main processor in order to determine the location of the origin of the signal. In detail, this process would be done with the implementation of hardware with the capability to oscillate, on and off, the transmission of a 4 kHz acoustic signal. This signal then would be picked up by a receiver. Then by using a transducer, in this case a microphone, the next circuit would transform the acoustic signal into an electrical signal. Then the circuits would filter out unwanted noise from the signal and send the desired frequencies to the radio antenna where they would be transformed into an electromagnetic wave. This wave would then be sent to the central processor on the beach.

3.7.1 The Band Circuit

The band was solely comprised of two different 555 timers which worked in series to pulse a 4 kHz wave through the water.



A: 555 Timer Chip



B: How the 555 Timer is Displayed in a Circuit Diagram

Figure 54: The 555 Timers Chips

The 555 Timers displayed in

Figure 54 are a type of op-amp, a standard 555 timer chip has 8 pins with their functionality shown in

Figure 54A.

Figure 54B shows the standard way 555 timer chips are depicted in circuit diagrams. 555 timers can further be broken down into three subclasses or specific configurations; Monostable, Astable, and Bistable. In the Monostable mode "the 555 (Timer) functions as a one-shot". In the Astable or "free running mode: the 555 can operate as an oscillator." Finally in the "Bistable mode or Schmitt trigger: the 555 can operate as a flip-flop, if the DIS (Discharge) pin is not connected and no capacitor is used". The three configurations are illustrated in further detail below in

Table 5 shows the three different modes of a 555 Timer, the common name of those modes, and the some of the common uses of the individual timer types.

Table 5.

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Table 5: The functionality of a 555 timer

555 Timer	Monostable	Astable	Bistable
Name	One-shot	free running mode	Schmitt trigger
Applications	timers, missing pulse detection, bounce free switches, touch switches, frequency divider, capacitance measurement, pulse-width modulation (PWM)	oscillator, LED and lamp flashers, pulse generation, logic clocks, tone generation, security alarms, pulse position modulation	Flip-flop switch, bounce free latched switches

A requirement of the band design was ability to repetitively send out a four kHz signal. Research of precedent designs allowed for the conclusion that the simplest configuration would be to use 555 timers exclusively. In order to design a four kHz wave generator it was determined that an Astable, or free running timer, was required. This requirement was set because 555 timers in the Astable mode are essentially an oscillators. By definition this means that the timers will act as a tone generator.

$$\boldsymbol{F} = \frac{\mathbf{1.44}}{(\boldsymbol{R}\mathbf{1}+\boldsymbol{R}\mathbf{2})\times\boldsymbol{C}\mathbf{1}} \qquad 3$$

Using 3 and setting up the 555 timer in the same configuration as shown in Figure 55, the process of configuring a design where the 555 timer oscillates at 4 kHz is easily achievable. When this circuit was then attached to a microphone, a 4 kHz acoustic waveform would be produced.

Equation 3 is the equation which determines the output oscillation frequency of a 555 timer in Astable mode. In the equation, F is the output frequency; R1 and R2 are resistors while C1 is a capacitor. R1, R2, and C1 are specific components laid out in their specified positions show in Figure 55.

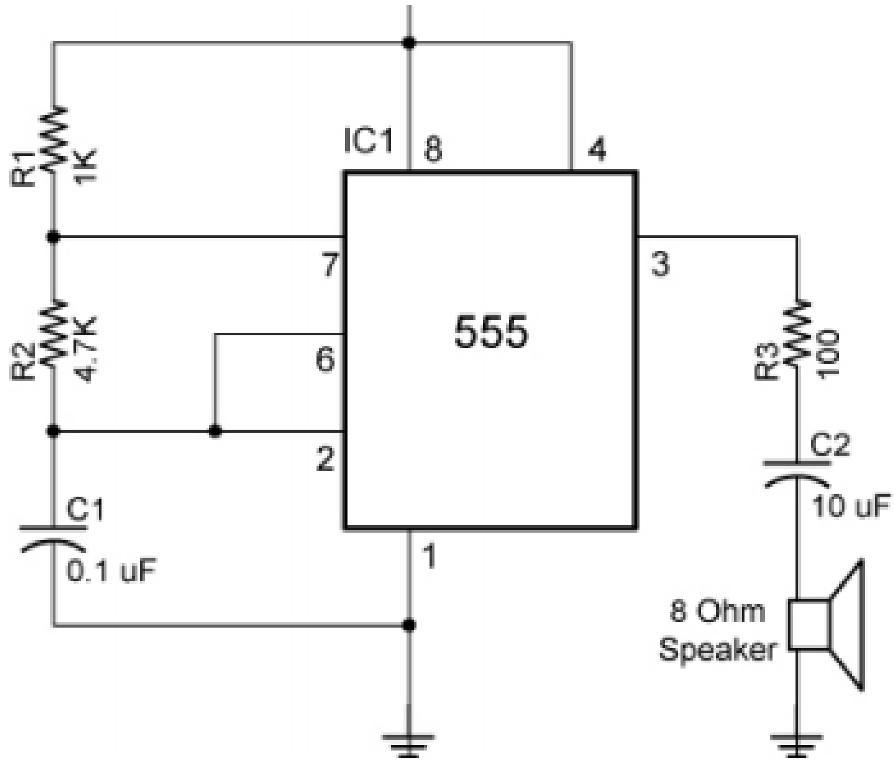


Figure 55: 555 Timer in Astable Mode

Figure 55 depicts the configuration of how a 555 timer is required to be configured in order to allow for use in the Astable mode. As previously stated, this mode allows for the timer to be used as a tone generator, the functionality necessary to produce the 4 kHz sound wave.

After the first step of completion of the band circuit had been, the 4 kHz sound wave producer, the next step was to develop a method to turn the acoustic wave on and off. Based on research of 555 timer operational functionality, it was determined the simplest process to complete this task was to implement a second type of 555 timer. The Monostable, or one-shot configuration, of the 555 fulfilled the requirement. The functionality this configuration enables is the ability to change output from high to low concluding a designated amount of time, meaning the output is either zero or the input voltage. Essentially the Monostable 555 timer has the ability to power a device for a determined amount of time and then turn the device odd for a second predetermined length of time. This functionality is constantly repeated in the design of the band circuit. 4, shown below, is the equation used to determine the length of time, measured in seconds; the output of the Monostable 555 timer was set for high.

$$T1 = \frac{1.1 \times Ra \times C}{1000} \quad (4)$$

4 was also used to calculate the time for a Monostable 555 timer. Where R is in Kilo Ohms and C is in micro farads. Ra is the resistor and C is the capacitor that is displayed in Figure 56.

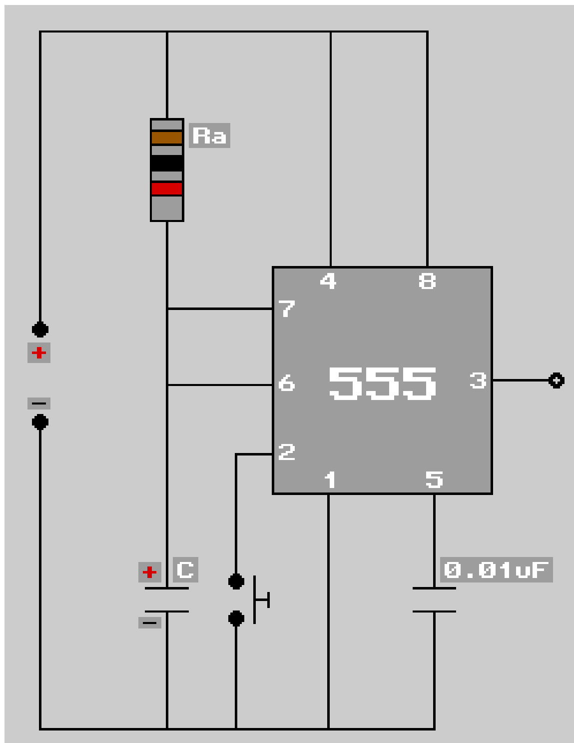


Figure 56: Monostable 555 timer

Figure 56 illustrates the Monostable version of the 555 timer. A comparison of the two versions of the timer circuits shows the Monostable verision is simpler because it contains two capacitors and one resistor. This version of the 555 timer would set a time limit that the other 555 timer could be on. This would pulse the 4 kHz wave that the other 555 timer was generating.

While the Monostable mode complied with all the necessary requirements, they could only be fulfilled by pressing a button. This limitation forced the design to be unable of continuously alternation between on and off states, only capable with a button compression. The design was then altered to no longer use a Monostable 555 timer but to instead use a second

Astable 555 timer. The second 555 timer was configured to continuously alternate between on and off, without the need for manual power supply.

In order to adapt to a new design, both 5 and 6 were used to calculate for the time durations for the timer to be set on high and to have an output of zero.

$$T_{high} = 0.693 \times (R1 + R2) \times C1 \tag{5}$$

5 was used to calculate the amount of time the output of the Astable 555 timer would be set on high. T_{high} represents the time in seconds while R1, R2, and C1 are resistors and capacitors shown in Figure 55.

$$T_{low} = 0.693 \times R2 \times C1 \tag{6}$$

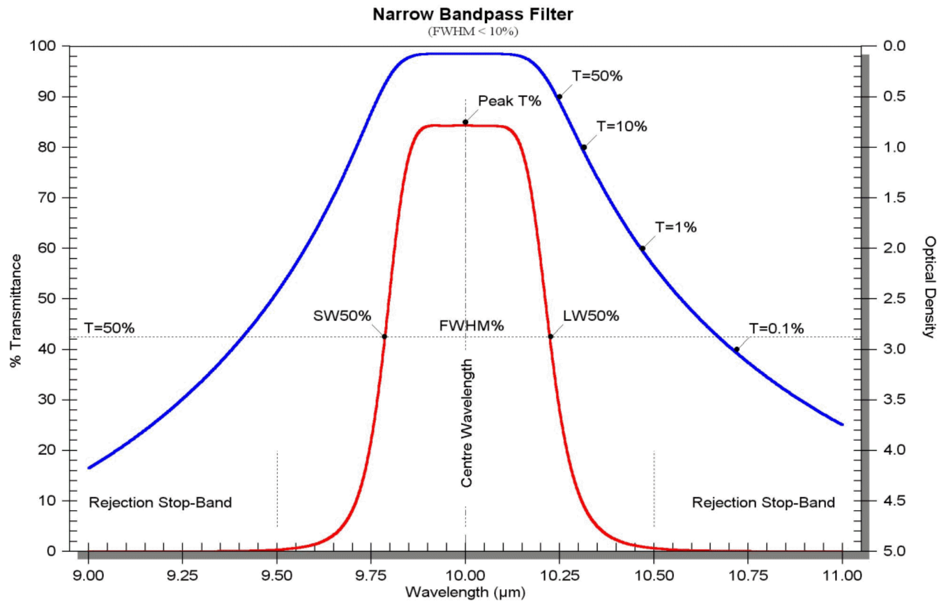
6 was the equation used to calculate the amount of time the output of the Astable 555 timer would be set to zero. T_{low} represents the time in seconds while R1, R2, and C1 are resistors and capacitors shown in Figure 55.

3.7.2 The Relay Buoy Circuit

The buoy is the component of the wireless system which takes in the signal, produced by the band, and transfers it from an acoustic wave to an electromagnetic wave. The filter required for the desired signal to pass through was determined to be a band pass filter. A band pass filter has a high and a low cut off frequency, allowing only the desired signal frequencies to pass through the filter. Initially a band pass filter was designed exclusively using 7 below.

$$Fc = \frac{1}{2\pi RC} \tag{7}$$

While this configuration to function, it was decided the rising and falling edges of the filter were not steep enough, depicted in Figure 57 with the blue line. This figure is a representation of how the configuration allowed for the desired frequencies to pass through, but how it also let through



an undesirable amount of other frequencies.

Figure 57: Band Pass Filter Frequency Graph

This discovery spurred to decision to use a more complex filter to eliminate a wider range of unwanted noise. From these conclusions a filter with a more steep graphical shape, shown by the red line in Figure 57 was chosen. The selected, more complex filter was designed with the use of Multisim and various built in components. It should be noted that Figure 57 does not represent a graph of the filters that were used in the final design. Multisim does not have the functionality to graph the filters it designs.

The second part of the relay buoy circuit was a non-inverting amplifier. Each buoy would have a different gain in order to ensure the amplitude of each signal generated would be different. 8 shows the method to change the output voltages of op-amps. Each relay buoys' R1 was kept at a constant resistance, across all of the buoys, while R2 was varied. This caused each buoy to have a different wave amplitude for the signal sent out. The reasoning behind the variations was so each buoy could be identified by analyzing the amplitudes of individual waves.

$$V_{in} = (1 + \frac{R2}{R1}) \times V_{in}$$

3.7.3 The Buoy Initialization Circuit

The final circuit designed was the initialization of the buoy. This circuit sent out an electromagnetic wave informing the receiver location on beach where each buoy was located. Being the last of the three circuits to be designed, it incorporating all prior research. Design of the circuit incorporated many aspects of the band circuit. Additions to the initial design were needed though to optimize the buoys for quick localization. Astable 555 timers, by design, require a longer time high than time low. A reference to 5 and 6 supports this statement. The time high incorporates an extra variable which cannot be a negative number. Requirement of a positive number causes the time high to always be greater than the timer low. In order to compensate for time difference, two additional op-amps were added to the circuit. An inverting amplifier was first added to the circuit, causing the signal to change from 0-12V to (-12)-0V. The output of the first op-amp was then sent though a summing amplifier, adding the output of the inverting op-amp to 12v. This amplifier changed the signal went from (-12)-0V back to 0-12V, but with an inverted duty cycle, meaning the length of time the signal was high compared to the length of time that it was low or zero. The addition of these two op-amps inverted the high and low time, causing the output signal of the initialization circuit to be on for a brief period of time.

3.7.4 The Finalized Band Circuit

The finalized band circuit, as seen in Figure 58, generated pings which were on for 3.465 seconds and off for 1.7325 seconds. This calculation was completed with 5 and 6 respectively. Using 3, it is proven the 4 kHz frequency could be produced using the 7.215 and 14.43 K Ohm resistors along with the 10nf capacitor.

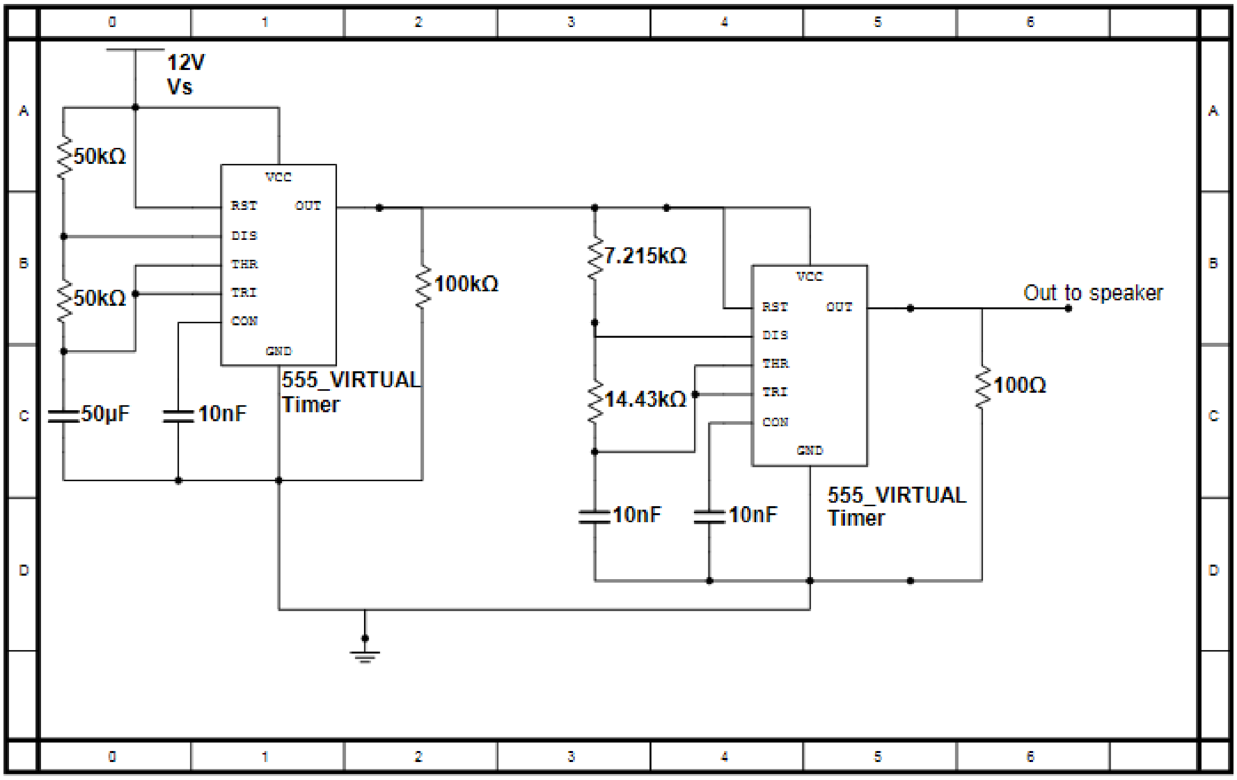


Figure 58: The Finalized Band Circuit

Figure 58 is shows finalized design of the band circuit using Multisim. This idealized version was implemented on a copper cover PCB board, shown in Figure 59 below. To use PCB board design of the circuit had to be first completed in Multisim, which then exports the design to Ultiboard. This program uses the design of a circuit, and allows for manipulation of components to be configured in any manner. The band the circuit was configured to have a design capable of fitting on one side of a PCB board. After the circuit was put designed in Ultiboard it was printed with a LaserJet printer onto a glossy paper. The paper was then ironed onto the copper side of the PCB board. This transferred the toner from the glossy paper to the copper. The PCB board was then set into a solution, one parts muriatic acid, two parts hydrogen peroxide. The solution dissolved any copper not covered by toner, depicted in Figure 59.

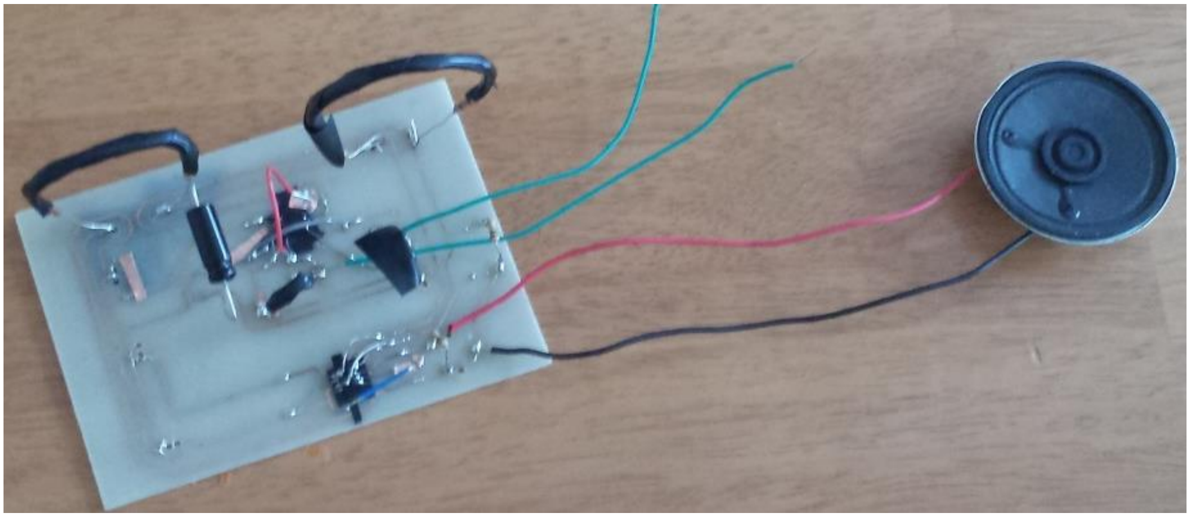


Figure 59: Final Implementation of the Band Circuit on PCB Board

Figure 59 is the band circuit, which can produce a 4 kHz sound via the speaker when a 12v battery is connected to the exposed ends of the green wires.

3.7.5 The Finalized Buoy Relay Circuit

The relay section of the buoy circuit was able to successfully filter signals, it allowed only for signals within the range of 3 and 5 kHz to pass through. The amplifier of this component of the circuit functional as designed too. It filtered signals and amplified the signal to desired wave amplitudes. Although timing restricted the testing of this circuit with the use of the microphone, the band was directly hooked up into the band circuit. Initially the buoy relay circuit was designed in Multisim, shown in Figure 60, as was designed to have a gain of 50. For testing purposes the gain of the op-amp was limited to a gain of 5. This allowed for the band to be directly connected to the band, but would have had to be increased again if the buoy was using the microphone.

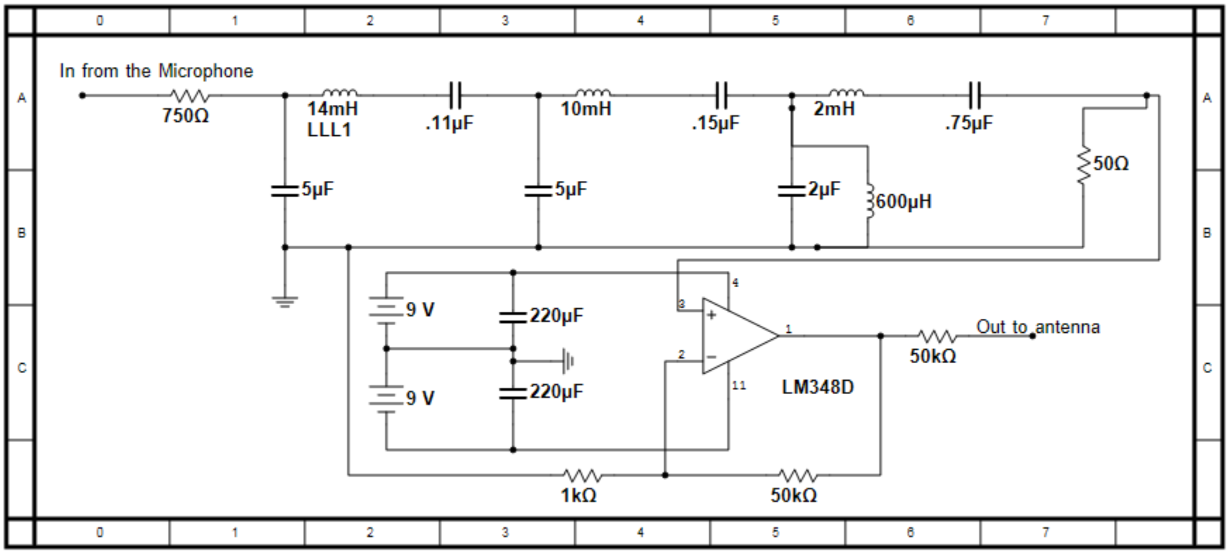


Figure 60: Buoy Relay Circuit

Figure 61 is shoes the final version of the buoy relay circuit, designed and laid out on a breadboard. The use of a breadboard was chosen to decrease build time in order to allow time for testing.

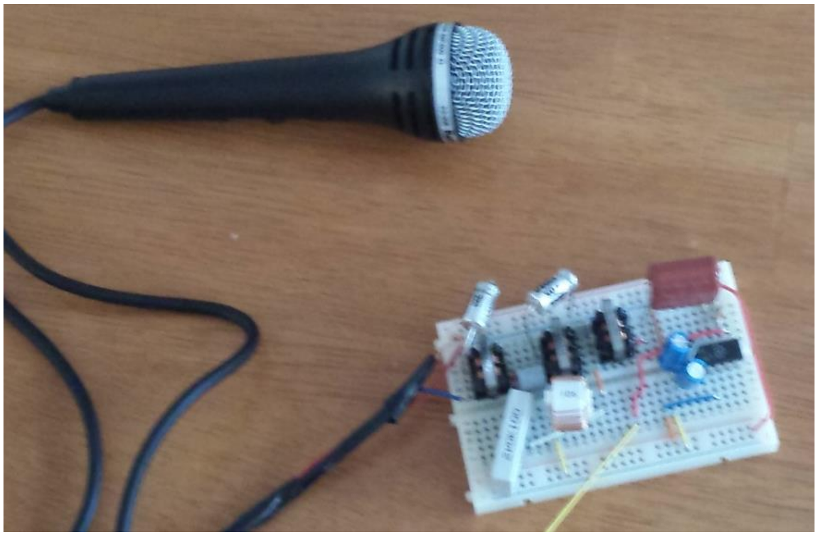


Figure 61: Buoy Relay Circuit Using a Breadboard

The breadboard was used to optimize the time between building and testing the component.

3.7.6 The Finalized Buoy Initialization Circuit

The buoy initialization circuit below, in Figure 62, illustrates the two 555 timers that produce the pings of the waves, and the two op-amps that which have the time high of the first timer less than the time low.

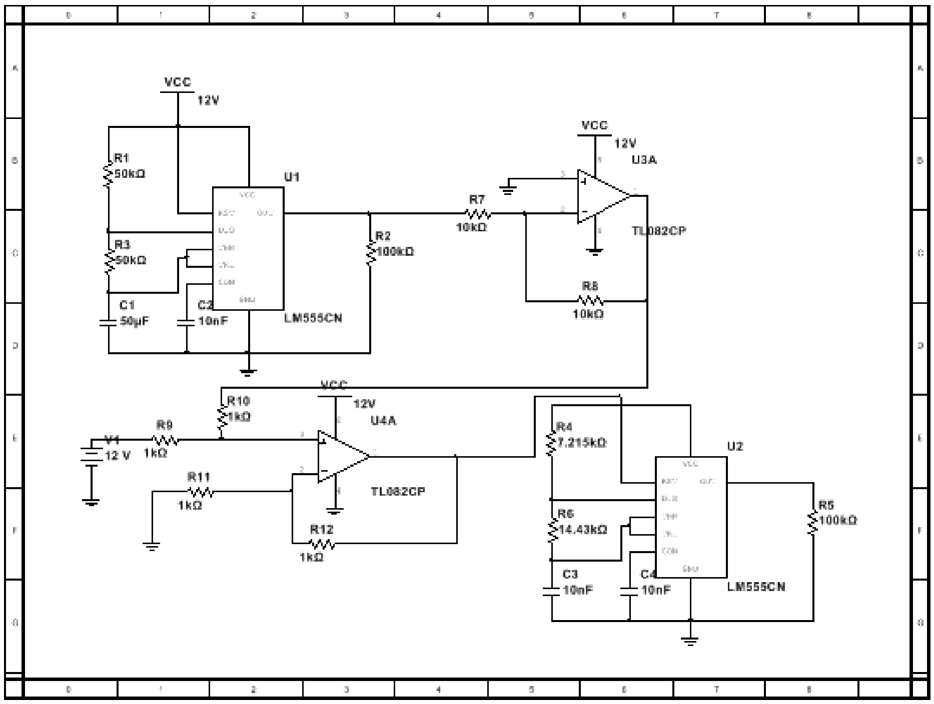


Figure 62: Buoy Initialization Circuit

3.7.7 Real Time Signal Processing for the Wireless Signals

In order to allow full use of wireless communication between circuits the signals needed processing, which was completed using Matlab. This program has a built in functionality which uses Fast Fourier Transforms (FFT) to convert signals from the time domain to the frequency domain. This was processed in real time by importing the signals into Matlab via USB. The calculation of the amplitude of the waves was completed by finding the max in the time domain; likewise the frequency was found by finding the max in the frequency domain. The real time processing of the signal was able to be fully achieved and signals from different buoys were able to be distinguished from each other.

3.8 Software Architecture

While it is not the most visible component of the BUDD-E System, the software that drives the communications processes, handles swimmer monitoring, and executes robot control is both complex and mandatory for the system's overall success. The software was initially developed for internal functionality, with the gradual addition of support for peripheral communication devices necessary to full-system integration. The software execution is carried out on two separate processors, one doing most of the heavy lifting at the beach base station and

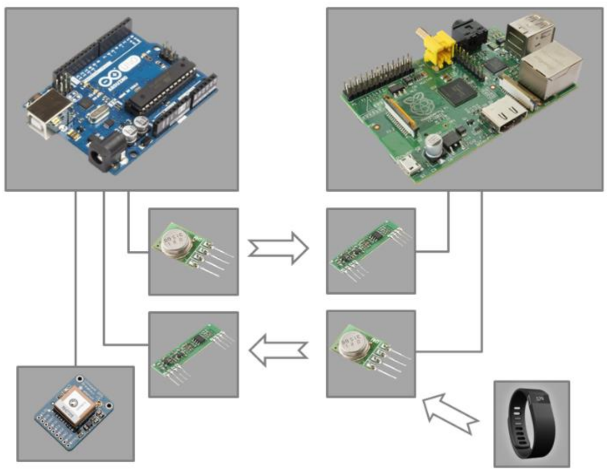


Figure 63 - Diagram of Arduino Uno and Raspberry Pi and peripheral communications devices.

a second processor governing robot control. The multi-processor split was deemed necessary to allow the system to operate in real time, as communicating behavioral priorities for the robot's operational state is vastly preferable to treating the robot as a remote-control boat driven by the processor on the beach. The hardware utilized in the BUDD-E System design is shown in Figure 63, with a detailed explanation in the following section.

3.8.1 Sensing & Processing

The majority of necessary computations are carried out by a Raspberry Pi, filling the role as the base station on the beach, while all of the code responsible for the robot's behavior is executed by an onboard Arduino Uno. Each processor both transmits and receives data via radio-frequency with the rest of the system, and the Uno also takes in position data from a global positioning system (GPS) card. While the functional output of the Uno is a control signal that governs the speed and direction of the robot's motion, the Pi's primary role is to output swimmer pulse and position data via Bluetooth. This data is intended for use by lifeguards using a dedicated smartphone or tablet computer application to monitor swimmers within the boundaries of their assigned beach. The overall system of processors and peripheral devices, as well as the wireless communications between the wristbands and processors are shown in Figure 63.

The beach processor software was designed to perform three major functions. The first is to triangulate each component of the system using the transmission-to-reception interval timing while determining corresponding GPS coordinates. The second function is to take in signals encoded with swimmer pulses and detect potentially problematic trends among them. Finally, the processor is responsible for coordinating communication between the lifeguard application and the robot behavior control.

The robot processor software was written to exhibit two primary behaviors while maintaining a current map of swimmer positions. The first behavior is a standby-mode operation in which the robot stays farther from the beach than swimmers while staying as close as possible to the centroid of swimmer positions. The second behavior is an emergency rescue mode triggered automatically by the system or manually by lifeguards, and in this mode the robot navigates to a specific swimmer to support them in the water and bring them to land if need be. While either of these behaviors are executed, the robot is also responsible for detecting obstacles in its path and avoiding collisions.

3.8.2 Data Simulation

One issue encountered early in the development process was that much of the software depends on filtered data from the custom circuitry in the wristband and relay buoy peripherals. This presented challenges for developing the software in tandem with the circuitry, and it was unrealistic to wait for the circuits to be finalized before writing the software if the project could be expected to be functional within the allotted time period for development and testing. To circumvent this problem, it was decided that the input signals from the custom peripherals should be simulated in the code. Once the circuitry was complete, the buoys would be able to interface with the Raspberry Pi via radio signal and the analog input could feed the signals into the code in place of the hard-coded example data used as functional place-holders.

To accomplish this, a file was created containing sample values for 15 test-case individuals entering and leaving the water over a period of one hour. Each simulated swimmer was programmed to exhibit various behaviors that the system will need to monitor in practice, ranging from regular swimming activity to an individual experiencing a heart attack. This allowed for error checking in the status-determination code by creating edge cases and as the simulation was run, it would hit cases attempting to force the system to save multiple swimmers at once. This sort of testing would not be possible with a physical system reporting raw data from physical swimmers, so this was an added benefit of developing the software prior to the rest of the system's completion.

Each individual was attributed with a position on the simulated beachfront in addition to the other data that would normally be received by the Raspberry Pi for processing. A visual example of how the raw simulated data differs from data as it would be transmitted in practice is shown in Figure 64.

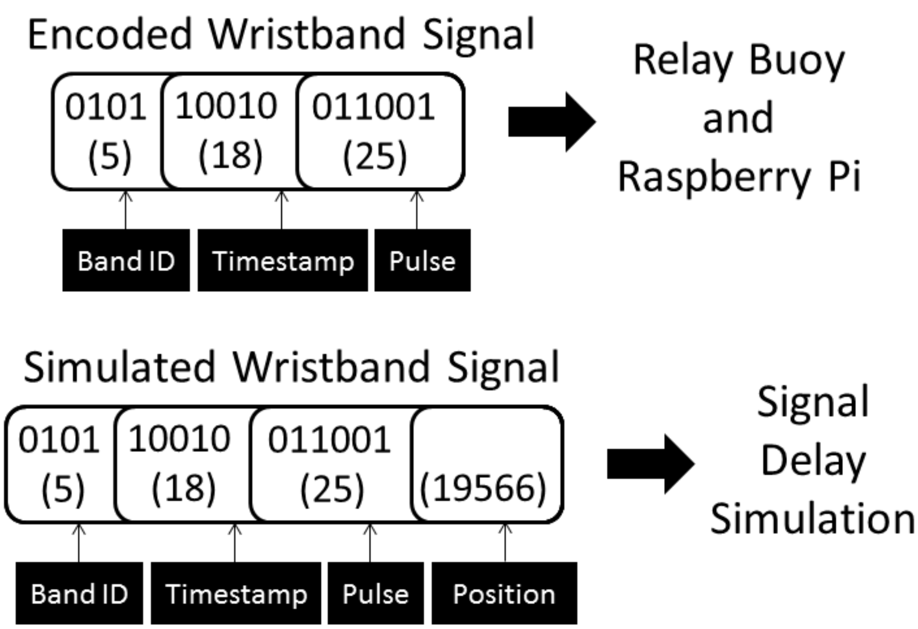


Figure 64 - Comparison of example input data for the physical system and the simulation.

This data was then queued by a pre-simulation process dedicated to calculating signal arrival times based on the simulated point of origin in the water. To do this, the process found buoys in range of the wristband's ideal acoustic signal (60 feet), and calculated travel times to each buoy based on the speed of sound through saltwater (5,118 feet per second at 3 feet of depth and water temperature of 68˚F). Time-of-flight between the relay buoy and the Raspberry Pi was considered negligible for radio-frequency signals traveling distances of 100 to 1324 feet. Once the pre-queuing code had arranged each signal in order of reception, it created a reference file containing the simulated wristband signals along with the time at which the code should receive them. Upon simulation start, this was then supplied to the simulation software as though it were arriving through an analog input port at the prescribed time after the simulation's start. The data was then handled by the pulse monitoring and triangulation processes as normal.

3.8.3 Pulse Tracking

Heart rates for active humans of various ages and levels of physical fitness range from 80 to 200 beats per minute, which translates to 1.3 to 3.3 beats per second. As the wristbands send a ping of data every 3 seconds, it was calculated that simply relaying beats per ping resulted in a potential error of up to 20 beats per minute. Instead, the system was designed to relay the number of beats in the last 15 seconds, every 3 seconds. This resulted in a value between 20 and 50 beats per ping, with an accuracy of 4 beats per minute. This allowed the BUDD-E System to sufficiently distinguish different trends in pulse data for test swimmers, with some sample pulses illustrated in Figure 65.

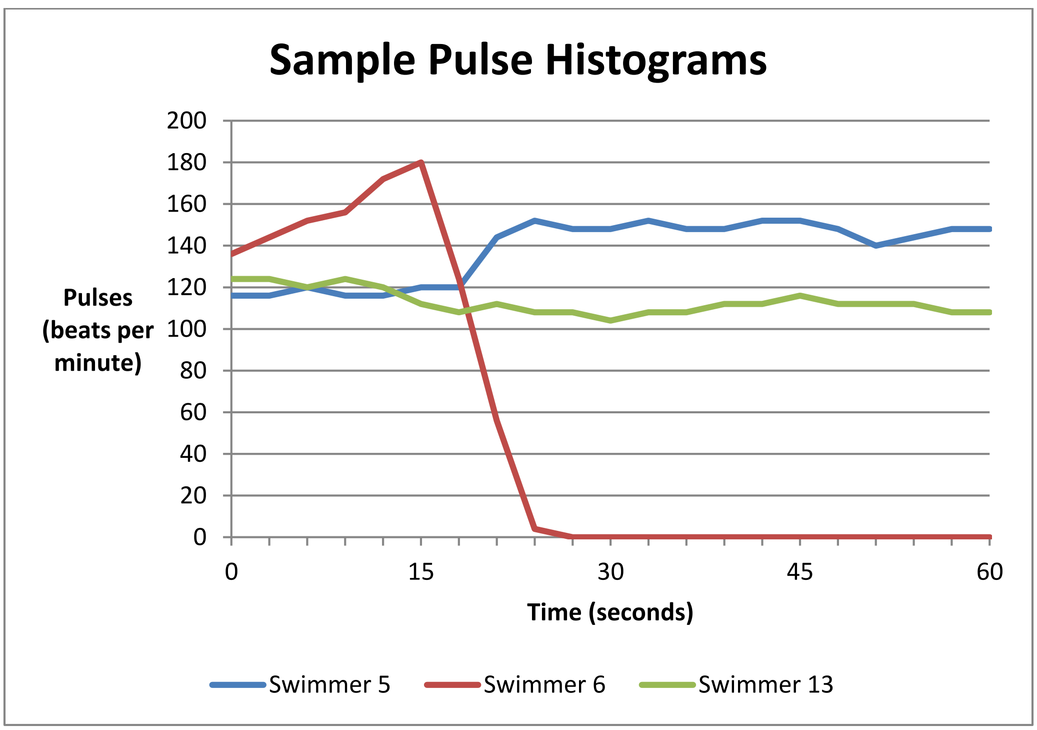


Figure 65 - Examples of sample pulse data in the span of one minute.

Upon recognition of a ping from a given wristband, the software would convert from beats per 15 seconds to beats per minute, record the result, and compare it with the preceding 30 seconds of values. Based on this comparison, the software would flag swimmers whose pulses exhibited trends indicative of impending problems as requiring focused lifeguard supervision. Any swimmers whose pulses exhibited extreme anomalies or prolonged heart rates elevated past 125% the average of their past 10 heart rates were flagged as emergencies. This accounted for those who may simply be casually exerting themselves while maintaining a threshold for those whose pulse speeds up drastically due to fear and a struggle to stay afloat. By focusing on changes in an individual's pulse over time, the system is able to account for the massive variety present in the typical human heart rate.

3.8.4 Triangulation

The beach software was designed to triangulate swimmer positions in conjunction with tracking their pulses. To do this while also maintaining a common frame of reference with the robot, the software generates a 100-foot by 2640-foot topographical grid with a scale of one square per foot. This simulates the first 100 feet out from shore along a half mile of coastal beach. Each square has coordinates indicating its position in the grid and an integer value encoding the contents of the square to the best of the software's reckoning. The square containing the Raspberry Pi defines the square of coordinates (0, 1320), and is assigned a constant value of -3. In addition, two empty arrays of objects defined as "pings" are initialized, one for intake queuing of up to 100 pings, and a 15-by-3 two-dimensional array of pings to carry the three most recent pings for each wristband being simulated. As signals are received by the Raspberry Pi, the triangulation process immediately assigns a timestamp to each signal that is received, creating a ping object with fields for a wristband identifier, a relay buoy identifier, a transmission timestamp value, a reception timestamp value, and a pulse value. This ensures that in the event that the calculations are not completed immediately, the timing of the signal reception is preserved with accompanying data when the calculations are finally performed. Once the incoming ping is given a timestamp, the code then uses the wristband identifier to sort the ping into the 15-by-3 ping array, compare the new ping's buoy identifier value and timestamp values with those already stored, and overwrite an old ping with the new. If the new buoy identifier matches an old one, the matching ping is overwritten. If not, the ping with the least recent transmission timestamp is overwritten in favor of the new ping.

Alongside this sorting algorithm, a second process thread iterates through the 15-by-3 ping array and for each wristband, calculates the most probable square in the topography grid for the wristband to be in. The thread starts by comparing each of the three pings using the difference in reception timestamps adjusted by the transmission timestamps.

3.8.5 Robot Behavior

The BUDD-E System robot has two primary modes of operation, standby and emergency rescue. In standby mode, the robot maintains a distance from shore of approximately 85 feet, and adjusts its position along the shore to minimize its distance from the average position of swimmers (hereafter referred to as the swimmer centroid). Following the swimmer centroid maximizes the robot's preparedness to navigate to any given swimmer in the event that they require assistance. In emergency rescue mode, the robot executes a path planning algorithm to find the quickest route to the target swimmer by minimizing drastic direction changes and avoiding obstacles.

The path-planning algorithm is a relatively simple one. After updating the robot's current position and its target position, the software implements an A* search algorithm to determine the shortest obstacle-free route to the target position. Since the robot dimensions are 10 by 5 feet, all obstacles are given a buffer of 8 feet to accommodate for half of both the maximum width and length of protrusion from the robot's center, as well as a few feet of error to ensure collision prevention. Once a path is determined, the path is converted from a series of consecutive target squares to a set of forward movements and turns. In the process, the result was adjusted when possible to smooth out turns and minimize the breaking necessary to reach the desired position with all haste.

While the software was only operated in simulation, in order to prepare to control the drive system it was necessary to utilize three of the Arduino Uno's output ports. One dictated the propulsion motor speed, one controlled the steering servomotor, and the third controlled the reverse-trigger servomotor. Propulsion motor voltage was proportional to the distance to be traveled between turns, and while steering angle, propulsion reverse, and motor speed were adjusted relative to one another during turns depending on how sharp the prescribed turn was.

These behaviors help streamline the robot's path to leverage its ability to move forward very efficiently at the loss of powerful, responsive turning.

Instances in which more than one swimmer could conceivably occur in practice, so such a situation was included in the simulation. When multiple goal locations are received from the rest of the BUDD-E System at once, the robot prioritizes rescuing targets farthest from the beach, those located near each other, those located near the robot, those whose alarm is based on dangerous pulse trends, those in concentrated locations, and finally those whose alarm is based on position changes.

3.8.6 Lifeguard Application

In addition to tracking and assisting swimmers, a full implementation of the BUDD-E System also keeps lifeguards informed of swimmers' locations and ability to swim safely. While this aspect of the system was not developed, parameters for its operation were determined to facilitate future development. The beach processor and robot both have calculated GPS positions in real time, and from these the processor can calculate swimmer GPS coordinates as it determines their positions. These coordinates, along with swimmer pulse data, can be securely sent via Bluetooth to a tablet computer or mobile phone which can take the data in and overlay color coded icons on a Google Earth view of the beach being monitored. A mock-up of this application is shown in Figure 66, in which the square, circle, and octagon indicate the robot, processor, and buoy locations respectively, and the stars represent swimmers positions.

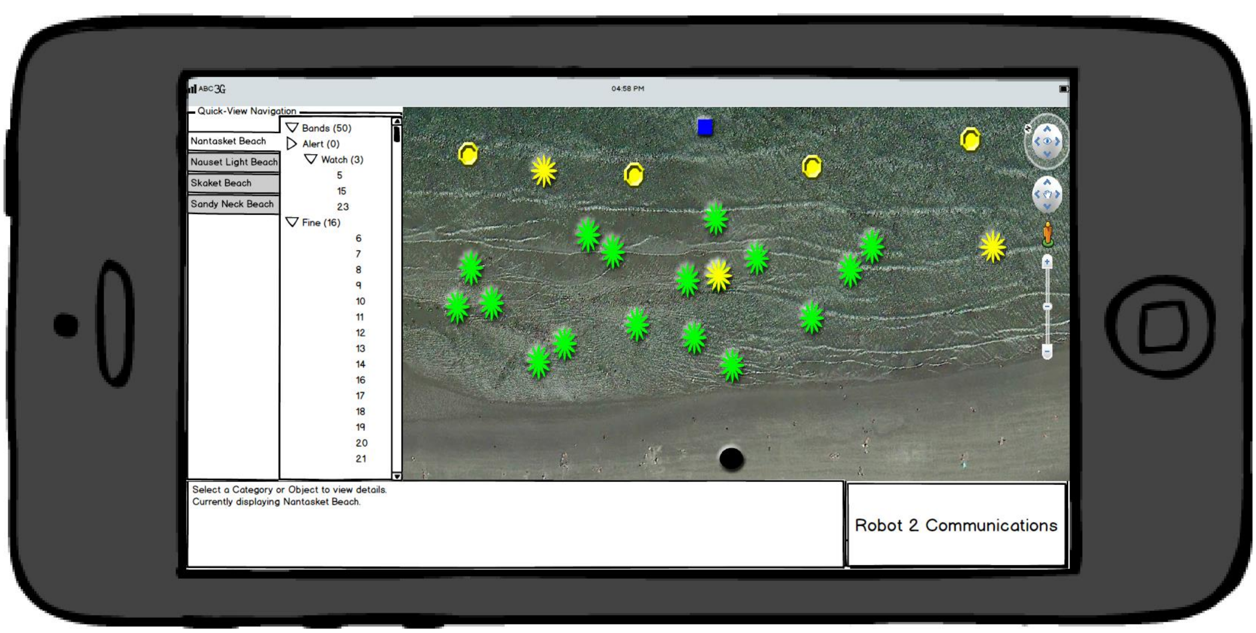


Figure 66 - Lifeguard application mock up.

In the mock-up, green stars are swimmers whose pulses are not exhibiting problematic trends and whose positions in the water are not indicative of a need for assistance. Yellow stars distinguish swimmers who might have experienced cardiovascular trouble, are approaching the boundaries of the BUDD-E System's ability to monitor their safety, are moving out to sea in a manner that may indicate the presence of a rip current, or are isolated from other swimmers and should simply be paid special attention to ensure their safety. Finally, if any swimmer should manually activate the beacon on their wristbands, exhibit a trend of an excessively elevated heart rate, or experience a heart attack, their icon will turn red and automatically trigger assistance from the robot.

Presented with this interface, lifeguards are able to select individual swimmers to view pulse histograms, total swimming durations, and to dispatch the robot to a particular swimmer if desired. In addition, the interface can provide quick access to 911 emergency response in the event of a potential drowning incident. In addition to these features which would provide unprecedented amounts of information to lifeguards in real-time, additions could be made to facilitate the lifeguard's ability to monitor swimmers. A microphone and speaker system could be added to the robot payload to allow a lifeguard on the beach to communicate through the application with swimmers in the water or rescued swimmers using the robot for support. While this would increase the demand for bandwidth in the system communications, it could be facilitated if deemed worthwhile by lifeguarding staff at early-adopters of the system. This and other features could be added and tested as necessary, but care would need to be taken to avoid distracting from the main purpose of the BUDD-E System, to quickly and safely prevent drowning incidents at the beach.

Chapter 4 Results

4.1 Introduction

It takes as little as 20 to 60 seconds for a person to drown; with in these twenty seconds the person in distress is very rarely able to call for help, or help themselves. Approximately 50 percent of drowning incidents occur in open water settings, and with reasonable safeguards in place, almost all of them could be prevented. On average, of 3,650 people die each year from drowning, and 1/5 of those deaths are children. Drowning can still happen in cases when there is a life guard present, although the chances of survival are much higher for drowning victims with a lifeguard on duty. The two main problems faced by lifeguards are recognizing and locating a person who is in distress, and then getting to their location to rescue them. This second challenge is made more difficult because a distressed swimmer will inadvertently endanger a rescuer by flailing in the water and preventing the rescuer from being able to move effectively through the water.

The undertaking for this project was to develop a system that would aid a lifeguard in their line of duty. The system was required to integrate seamlessly with tried and true lifeguarding practices. The final result was the BUDD-E System. This system was developed to be able to locate a distressed swimmer and provide a flotation support robot within the 20 seconds that a person typically has before drowning. Once the BUDD-E System was at the distressed person's location it would also be able to act as an aid for a lifeguard by indicating the location of the distressed individual and acting as an autonomous flotation device. Ideally, the robot would arrive in time to allowing swimmer to climb aboard and ride to shore, but even if the swimmer is unconscious upon arrival, the robot can provide a lifeguard with an expeditious means of transporting the drowning victim to land for lifesaving procedures.

4.2 The BUDD-E System

Four co-dependent parts comprise the BUDD-E System: a wireless localization system consisting of a pulse oximeter wristband to be worn by swimmers and static buoys that boost the wireless signal, a central processing unit that controls the overall system behavior, an autonomous boat that navigates to swimmers in need of assistance, and a mobile tablet application to be utilized by lifeguards that will provide them with an interactive map of swimmers and their ability to swim safely. As shown in Figure 67, the system starts off by transmitting an acoustic ping from the wristband circuit, which is worn by every swimmer. This ping is then received by the buoy circuitry, where it is filtered and transmitted via radio

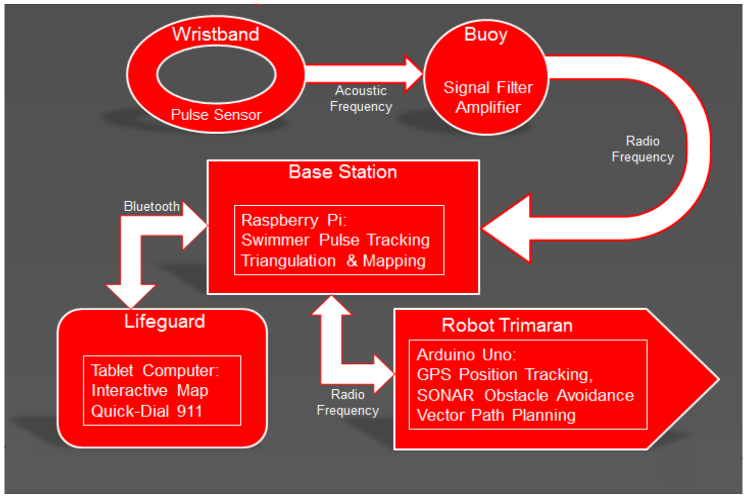
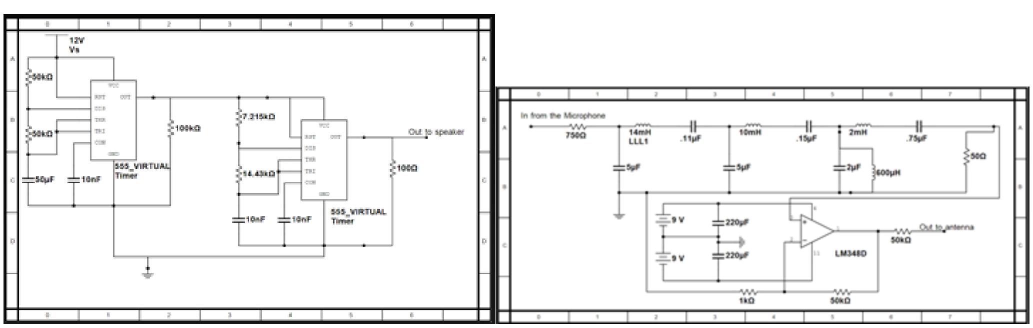


Figure 67: The Overview of the BUDD-E System

waves to the central processing unit on land. This processor will in turn collect the signals sent from each buoy and use this information to determine the location of the every active swimmer. Once these locations are determined, the beach transmits the calculated data as GPS coordinates to the robotic boat. The robot receives these coordinates, then uses them to plan and follow the quickest and safest path to any person determined to need assistance.

4.3 Implementing the BUDD-E System

The localization system for the BUDD-E System required development of two custom circuits, one for the wristbands and the buoys. The final circuit schematics can be seen in Figure 68A and B, respectively.



A: The wristband circuit.

B: The buoy circuit.

Figure 68: Wireless localization circuits.

The wristband circuit produces an acoustic wave encoded with the swimmer's pulse, or an emergency signal if the wristband is activated by the swimmer to call for help. The buoy circuit receives the acoustic signal and relays it to the processor on the beach via radio waves.

A Raspberry Pi was selected as the beach processor, and takes in the radio signals from the buoys and determines the location of the band through time-of-flight triangulation. These locations are then sent out as GPS coordinates to the robot.

The two primary goals for the design of the robot were speed and stability. This was because it needed the capability to both reach struggling swimmers before they drown and also be steady enough in the ocean to allow a person to climb on top of it. With these goals in mind, the final design for the robot was a trimaran, shown in Figure 69. A trimaran is a three-hulled boat, a design which gives the robot maximum roll stability relative to optimal hydrodynamic drag thanks to minimal surface area below the waterline.

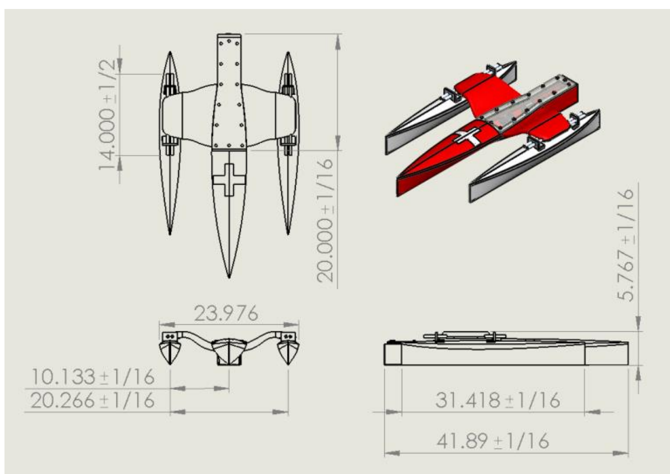


Figure 69: The final design of the robot.

The final component of the system was the proposed mobile application in Figure 70, providing the location and safety status of each swimmer in the water as color-coded icons on the beach.

Figure 70 - Proposed mobile application for lifeguards.

4.4 The Results

The BUDD-E System worked as expected, with only a few minor fixes necessary. The wireless localization system was able to produce the acoustic wave, filter and then amplify that wave, but sending the signal to the beach was untested. The beach processor was able to successfully simulate the data from 15 different bands at one time; this incorporated the changing safety status of each swimmer, and calculating the location of each swimmer over time. Initial tests of the robot revealed that there was a pinhead-sized leak in back of the boat's hull. This leak was located and sealed, and at that point the robot was able to traverse on the water at speeds exceeding the target maximum of 20 mph, with Figure 71 showing an image of the robot during this final test.

Figure 71 - Final test of the robot.

4.5 Future Work

While the BUDD-E System is functional there is still room for further development. The wristbands and the relay buoys need to be tested in conjunction with the beach processor, and the beach needs to be able to take in a signal and find its origin location. The robot needs to be fully integrated into the autonomous system. Finally, a full scale robot needs to be built and tested, and an in-depth market feasibility analysis is required to determine the ability for a product like the BUDD-E System to be successful on the open market.

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