SEATURTLE: Sustained Engagement Autonomous Tracking of Underwater RepTiLEs

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SEATURTLE

Sustained Engagement Autonomous Tracking of Underwater RepTiLEs

by

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Abstract

While oceans cover the majority of our planet, these vast expanses remain relatively unexplored. Among the most interesting parts of the ocean are the shallow reef systems, which contain a huge amount of the planet's biodiversity. The Sustained Engagement Autonomous Tracking of Underwater RepTiLEs or SEATURTLE is a low cost Autonomous Underwater Vehicle designed to carry out missions in these shallow environments. Its small displacement and precise movement make it ideal for navigating tight spaces, and its package of sensors make it easily adaptable to a variety of missions. For this project the vehicle was configured to autonomously track tagged objects underwater, using image recognition and the April Tags system.

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Introduction

The ocean is an immensely large space. Combined the oceans account for 71% of the surface area of the plant yet more than 95% of the underwater world remains unexplored.[1] While the majority of the ocean is cold, dark, and deep, a small portion contains incredibly diverse and densely populated coral reefs. Accounting for a mere 0.015% of the entire area of the ocean, coral reefs contain more than 25% of the ocean's biodiversity.[2] There is a tremendous amount we can learn from these shallow reef environments, but there is currently a lack of low cost, easily deployable solutions for conducting research on a large scale in these environments. Common research tasks include mapping of the underwater topography, counting the number of a certain species, tagging and monitoring animals, analyzing environmental characteristics such as temperature, salinity, or turbidity, among many others. In order to gather data researchers need a way to place their instruments in these aquatic environments. This can be accomplished in a number of ways, primarily through the use of human divers, remotely operated vehicles (ROVs), or Autonomous Underwater Vehicles (AUVs).

Using human divers to conduct research is both costly and relatively limited. Nitrogen buildup in the blood due to the increased pressure underwater limits humans to 160 minutes at 10m and only 5 minutes at 40m below the surface before specialized equipment and techniques must be used.[3] In addition hiring a commercial diver to conduct research comes at a median cost of $22 an hour according to the US Department of Labor.[4] Due to these limitations and costs it is generally much more desirable to use a robot to gather data. Remotely operated vehicles (ROVs) are very popular in both research and commercial projects, and are capable of running for many hours at extreme depths. ROVs are limited by the need to have a human at the controls at all times which increases operating costs and

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[1] (NOAA n.d.)

[2] (NOAA n.d.)

[3] (National Associaiton of Rescue Divers n.d.)

[4] (US Department of Labor n.d.)

since they are almost always connected to the surface through some form of tether, their range and mobility is limited. Autonomous underwater vehicles (AUVs) are similar to ROVs except they operate with little to no human guidance. This makes them particularly appealing to research missions because, once programmed, they can operate for a long period of time over large distances.

While AUVs are an ideal research tool there are currently few vehicles suited for conducting missions in and around shallow coral reefs. Most commercially available AUVs are designed to handle hundreds or even thousands of meters of depth and conduct missions over many hours, which not only greatly increases their cost, but also makes them too large to easily navigate delicate coral reefs.

The SEATURTLE platform is intended to conduct missions that larger AUVs cannot. While the vehicle is unable to attain the depths of larger robots, its small size and maneuverability make it ideal for navigating delicate reefs, and its array of sensors give it the same autonomous abilities of much larger and expensive vehicles. The low cost will also make it possible for research teams to deploy several of these vehicles simultaneously to gather data over a large area. This report will detail the design, fabrication, and testing of the vehicle. For this initial prototype the design focuses on creating a vehicle that can be used to autonomously track tagged objects underwater using a camera on the vehicle; however the same vehicle will be highly extensible to a variety of missions in shallow reef environments that would be otherwise impossible to conduct with existing hardware.

Existing Solutions

Autonomous Underwater Vehicles have been used for commercial, research, and military purposes for decades, and they come in a variety of shapes and sizes. The current market leader in commercial AUVs is Bluefin Robotics.[5] Bluefin manufactures a variety of vehicles ranging from the massive Bluefin-21 at almost 5m in length and capable to operating 4,500m below the surface, to the 1.75m Bluefin-9, capable of operating up to 200m below the surface.[6] While these vehicles are adaptable to a wide range of applications, neither is particularly well suited for conducting missions in and around coral reef systems due to their size. Among commercially available vehicles, the IVER family of AUVs manufactured by Ocean Server would most likely be the choice for any researcher looking to gather data in a shallow reef environment. At 1.2m in length with a maximum depth of 100m the IVER 2 AUV[7] is better suited for conducting missions in shallow waters than the larger Bluefin vehicles, but it is still significantly larger than almost all reef dwelling organisms, and therefore it is unlikely that it would be able to safely navigate through any dense coral reefs. In addition the starting price of an IVER AUV is $50,000,[8] even though it is marketed as a "low-cost" platform.

Figure 1: IVER 2 AUV[9]

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[5] (Bluefin Robotics n.d.)
[6] (Bluefin Robotics n.d.)
[7] (Ocean Server n.d.)
[8] (Ocean Server n.d.)
[9] (Ocean Server n.d.)

Apart from these commercially available vehicles many research groups build their own custom AUV's in house. The Woods Hole Oceanographic Institution has developed a number of AUVs for different types of missions including a platform called REMUS.[10] This vehicle has similar size and performance capabilities to the IVER AUVs, and has been used to great success on a number of missions, but like all the other current solutions, it is still too large to safely operate in coral reef systems.

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[10] (Oceanographic Systems Laboratory n.d.)

Design Specifications

The goal of the SEATURTLE is to create a platform for conducting autonomous missions in shallow reef environments, something that current AUVs are all but incapable of doing. Specifically, the SEATURTLE will be used to autonomously track tagged objects, however it will be easily extensible to a wide variety of missions. In order to meet this goal the following specifications will have to be achieved.

Minimum Depth	1atm = 10m
Maximum Size	3000cm^3
Minimum Speed	0.5m/s = 1 knot
Steering	Zero Drift
Turning Radius	Zero
Tag Identification Distance	5m
Minimum Operating Time	160 minutes
Maximum Cost	$500

Table 1: Design Specifications

Minimum Depth

The minimum depth of 10m, which can also be expressed as 1atm, was chosen because this represents the point at which the pressure on the vehicle will be double the normal atmospheric pressure at sea level. This depth was selected for the proof of concept prototype because it will thoroughly test all of the seals without requiring highly specialized components or testing apparatus.

Maximum Size

One of the major drawbacks of currently available AUVs is their large size. In order to safely navigate the tight confines of coral reefs the vehicle must be of similar size to the organisms that inhabit the reef. The maximum size was set to be equal in volume to the parrotfish, which is found in tropical reefs all around the world.[11] They range in size from 30cm to 120cm with a median estimated volume of 3000cm^3.

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[11] (National Geographic n.d.)

Minimum Speed

In order to accurately track tagged objects the vehicle will have to be able to keep up with them. The target of choice for this device is the sea turtle, as it is by far the most interesting and exciting animal to track around coral reefs. The average swimming speed of the green sea turtle is 0.41 m/s.[12] Therefore a minimum cruising velocity of 0.5m/s was chosen in order to track sea turtles as they move around reefs. This is equivalent to a speed of 1 knot; for comparison the IVER 2 AUV has a maximum cruising speed of 2.5 knots.

Steering

Nearly all missions will require the vehicle to navigate in a straight line. It is crucial that the vehicle be able to maintain a straight course in a given direction in order to perform more complex behaviors such as tracking.

Turning Radius

One of the major advantages of this vehicle over existing solutions is its ability to safely navigate in tight spaces. In order to accomplish this the vehicle will need to be able to turn in place with a zero turning radius. This will allow it to better mimic the precise movements of biological organisms around the reef.

Tag Identification Distance

Due to greater attenuation of light and high densities of suspended particles, visibility is much lower in water than air. In shallow reef environments visibility beyond 5m will be more dependent on the weather and water quality than the tag itself. In addition to the distance threshold the vehicle must also be able to quickly process images to detect tags.

Minimum Operating Time

Apart from robots another method researchers can use to collect data are human divers. As discussed earlier humans can only spend a limited amount of time at depth before they risk serious medical consequences from decompression sickness. At 10m of depth, the target operating point for the vehicle, the maximum bottom

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[12] (Seaworld n.d.)

time for a human diver is 160 minutes.[13] In order to be a viable alternative the vehicle must be able to continuously operate past this limit.

Maximum Cost

Cost is one area where the SEATURTLE can show major improvement over existing solutions. With commercially available low cost AUVs starting at $50,000 it is unlikely that any research project would be able to deploy more than one or two vehicles. By keeping the cost low it will be much easier for researchers to deploy an entire fleet of vehicles to complete large tasks much more efficiently than a single expensive vehicle could. For this initial prototype the maximum cost has been set at $500, or 1% of the starting cost of commercially available solutions.

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[13] (National Associaiton of Rescue Divers n.d.)

Design

The design of the vehicle presents a unique challenge. It must be able to gather data on its surroundings, process the data, and act on it. In order to do this, the sensing, processing, and propulsion systems must operate in sync, all while being adequately protected from water, yet still accessible in case modifications or repairs have to be made. The design can be broken up into the following components:

- Inspiration
- Propulsion
- Sensing
- Processing
- Electronics
- Computer Vision
- Housing
- Software

Inspiration

The initial idea for this project was to take an already assembled remote controlled underwater robot and add a sensor package and microprocessor to make it fully autonomous. Modifying an existing vehicle is highly advantageous because the design could then focus primarily on the sensing and autonomous operation rather than the propulsion system and housing. In addition, using a mass produced vehicle body is almost always cheaper than manufacturing a complete prototype from scratch.

The first step in this process was to determine the appropriate vehicle to modify. It had to meet the maximum size constraints and be cheap enough to leave money in the budget for purchasing sensors and other components. These constraints limited the search primarily to toy submarines, intended for use in backyard swimming pools. Among the limited submarines available the two that best fit the size and budgetary requirements were the Swimline RC Submarine[14] and the 13000 Seawolf Class Model Submarine.[15]

	Swimline RC Submarine	13000 Seawolf Class
Price	$45	$90
Length	23cm	35cm
Propulsion	2 motors pods for X,Y travel that can rotate to control Z	Independent X, Y, Z motors
Control	Radio	Radio

Table 2: Remote Control Submarine Comparison

While both vehicles meet the size constraint, the Swimline RC submarine was selected due to its lower cost and propulsion method. Having two independent thrusters allows for more precise turning which satisfies another of the design constraints.

In order to understand the baseline performance of the submarine it was taken to a pool for testing. The top speed was measured at 0.4m/s, just below the target speed of 0.5m/s. While the independent thrusters should allow the vehicle to turn in place the controls are set up such that turns are executed by shutting down one motor and running the opposite motor at full power. This resulted in much wider turns than theoretically possible if the stopped motor could be run in reverse. The submarine controls its depth by rotating the thrusters and applying thrust to move up or down in the water. However, the vehicle loses radio communication almost immediately once below the surface, at which point the motors shut off and the vehicle floats to the surface. The loss of communication while submerged is not surprising, however it will have to be taken into account in the final design. The vehicle will have to be able to operate with no external input while submerged, and will only be able to transfer data while surfaced.

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[14] (Amazon n.d.)

[15] (Amazon n.d.)

In addition to pool testing a teardown of the vehicle was performed to better understand its design and operation. The submarine has a total mass of 420g and a volume of 600cm^3, making the vehicle positively buoyant, and therefore requiring constant downward thrust to stay submerged.

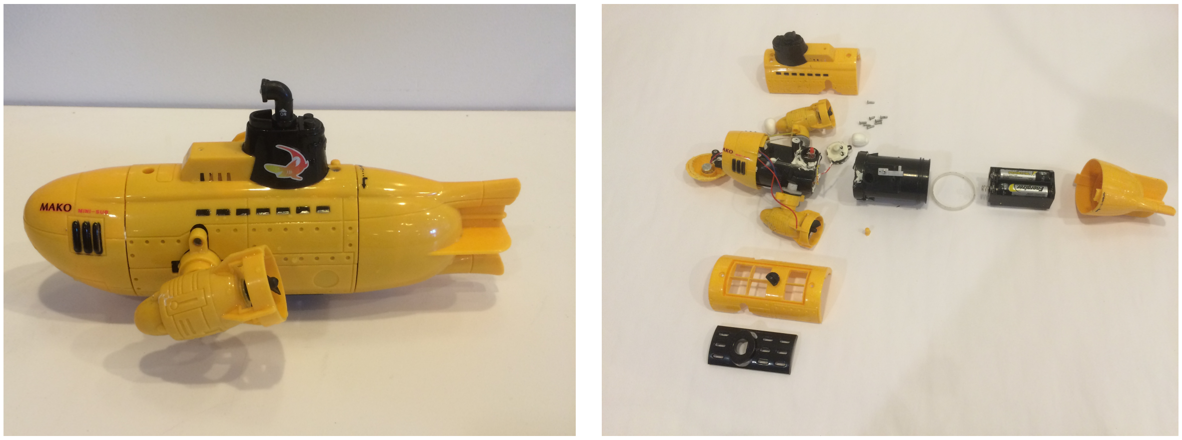

Figure 2: (left) Swimline RC Submarine, (right) Swimline RC Submarine Teardown

The teardown of the vehicle revealed the following components:

- 2 brushed DC motor pods with propellers
- 1 gear motor with integrated encoder for rotating the pods
- 6V (4AA) battery pack to power submarine
- On/Off switch
- Circuit board
- Headlight
- Outer unsealed shell
- Sealed inner compartment
- Ballast compartment

During the teardown it became apparent that the quality of construction of the vehicle is incredibly poor. Additionally, there is no space for adding components to the housing and all of the electronics are difficult, if not impossible, to interface with due to a lack of markings and the waterproofing compound applied to them. It became clear that the initial plan of adding components to this vehicle was infeasible. Instead, the Swimline RC Submarine served as a source of inspiration and parts for the custom designed vehicle.

Propulsion

The SEATURTLE's propulsion is based on the propulsion system of the Swimline RC Submarine. The vehicle has two motor pods, one on either side of the vehicle. The motors can be driven in the same direction for forward and reverse motion, and driven in opposite directions to turn the vehicle. This differential steering approach allows the vehicle to turn in place, satisfying the maneuverability specification of the project.

Figure 3: Swimline RC Submarine Thruster

Due to the size and budgetary constraints of the project there were very few options for motors. Most small-scale electric motor pods for underwater operation cost several hundred dollars and are equivalent in size to the final dimensions of this entire vehicle. Due to these limitations, and to prevent further increasing the scope of the project, the thrusters from the Swimline RC Submarine (Figure 3) were reused. While undersized for this vehicle, the thrusters are sufficient for a first prototype. The interface between the thrusters and the rest of the vehicle is designed to be easily adaptable to a new set of more powerful motors.

In order to control the depth of the vehicle two options were considered. The first option involves actively changing the buoyancy of the vehicle, causing it to sink or float. This method is commonly used in large AUVs as well as actual submarines, often by pumping water in and out of the vehicle. The other option is to rotate the thrusters up and down and use thrust from the motors to adjust the depth; the Swimline RC submarine uses the latter method to control its depth. While actively adjusting the ballast is the more accurate of the two methods, it is also far more complicated to implement, and it greatly increases the potential for a leak, which could lead to a catastrophic failure of the vehicle. In order to keep the project within a reasonable scope, depth is controlled by rotating the thrusters.

In order to rotate the thrusters two methods were considered, servos and a right angle gear motor. Servos allow for precise position control, however they consume a disproportionate amount of power and space. A gear motor will rotate both pods simultaneously and has no built-in position feedback, but it is much more efficient, and significantly smaller than servos. By adding an encoder to the motor the position of the pods can be tracked, making it a better solution than servos.

Figure 4: Tamiya 4-speed crank-axle gearbox[16]

The Tamiya 4-speed crank-axle gearbox (Figure 4) was selected because it provided the option for 4 different gear ratios, capable of delivering up to 17 Newton-meters of torque. It also has a built in worm gear to prevent any movement of the gears or

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[16] (Pololu n.d.)

thrusters while the motor is not running. Through testing, a gear ratio of 5402:1 was determined to be sufficient for rotating the thrusters.

One major drawback of the propulsion system on the Swimline RC submarine was the inability to drive the thrusters in reverse, which greatly reduced its maneuverability. However, since the thrusters are run with simple brushed DC motors, it is trivial to drive them in both directions using an H-bridge motor driver.

The L293D quad half H-bridge driver was selected to drive both the thrusters and the gear motor used for depth control. The L293D was selected because it can handle a maximum voltage of 36V and an operating current of 600ma per motor, which is above the 5V and 500ma operating point of all three motors used in this vehicle. It also allows for variable speed control of the motors using Pulse Width Modulation (PWM). Each L293D is capable of driving two motors independently; therefore a total of two will be used for this vehicle, one to drive both thrusters and a second to control the gear motor.

Sensors

In order for the vehicle to operate autonomously, it must be able to gather data about its environment and current state. The SEATURTLE gathers data from four sensors, an Inertial Measurement Unit (IMU), a pressure/temperature sensor, an optical encoder, and a camera.

Inertial Measurement Unit

The IMU is among the most important sensors for any underwater vehicle. Since GPS signal drops out almost immediately below the surface, and there are few identifiable landmarks underwater, vehicles have few ways of accurately determining their position. An IMU tracks the vehicle’s acceleration, orientation, and heading, which can be used for navigation and position tracking. The SEATURTLE IMU contains the L3GD20H 3-axis gyroscope and the LSM303 3-axis compass and accelerometer. The gyroscope provides the rotation of the vehicle, while the accelerometer provides its orientation relative to gravity as well as acceleration in each direction. The compass provides a heading relative to the magnetic field of the Earth, which can be used to perform navigation tasks. Accurate IMUs can also be used to integrate acceleration over time to determine velocity and position. However, this constant integration accumulates error over time, and for this particular IMU, testing showed that the accumulated error quickly overwhelms the accuracy of the readings.

Pressure/Temperature

Subsurface changes in depth are far more important than changes in altitude above the surface. For comparison, the pressure differential between sea level and 10m below the surface is equivalent to the pressure change between sea level and 5,500m above sea level. Due to this rapidly varying pressure it is very important to be able to sense depth, for both navigation and safety purposes. There are currently a wide range of pressure sensors commercially available, the majority of which are capable of handling pressures well beyond 10m below the surface, however most of them are not waterproof. In order to prevent the water from destroying the sensor it has to be isolated, but kept in a container that can accurately transfer changes in external pressure to the sensor. To test the viability of this system a BMP180 barometric pressure sensor was purchased. This sensor is capable of measuring pressure up to 11m (1.1atm) below the surface. For protection, the sensor was placed in a plastic tube with a thin rubber sheet covering one end, allowing the water pressure to increase the air pressure inside the compartment. Fabrication of this part proved difficult, and it was determined, that while significantly more expensive, a pressure sensor purpose built for underwater operation is better suited for this application.

Of the commercially available waterproof pressure sensors the MS5803-14BA was selected. It has a waterproof stainless steel casing, and can sense pressure down to 140m with an accuracy of 1cm. This sensor has also been used with great success with the Open ROV project.[17] While the body of the sensor is waterproof, the circuit

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[17] (Stackpole n.d.)

board to which it is attached is not. In order to protect the circuitry from water, the board was placed in an acrylic housing and filled with epoxy, until only the pressure sensing surface was exposed.

Figure 5: MS5803 -14BA pressure sensor in waterproofed housing

This sensor can also take temperature readings from -40 to +85 degrees C with 0.01 degree C resolution.

Encoder

As discussed in the propulsion section, the vehicle uses a right angle gearbox and motor to tilt the thrusters up and down to control depth. In order to operate autonomously the vehicle needs to be able to determine the angle of the pods. This is accomplished using an optical encoder. An acrylic disk with slots cut into it is attached to the rotating shaft of the gearbox. An emitter and receiver sit on opposite sides of the wheel, such that every time a slot passes between the two, the detector will receive a signal from the emitter. By counting the number of times the detector receives the signal it is possible to tell how many degrees the shaft has rotated. Varying wheel designs were prototyped with the number of slots ranging from 6 to 60. Eventually a wheel with 20 equally spaced slots was selected, with each slot corresponding to 18 degrees of rotation.

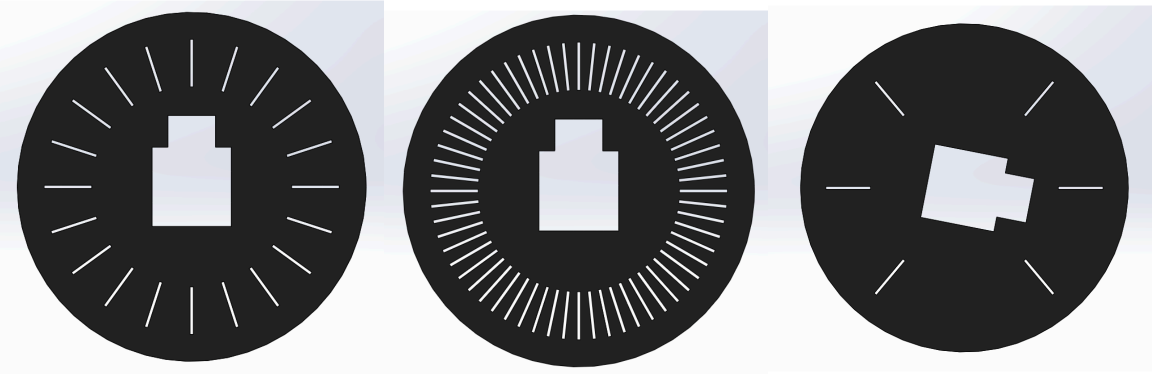

Figure 6: Encoder wheel designs: (left) 20 equally spaced slots, (center) 60 equally spaced slots, (right) 6 slots for set positions

Camera

To accurately track tagged objects underwater the vehicle has to be capable of seeing these objects. This is accomplished using a camera. The Raspberry Pi camera module was selected for this design due to its low cost and compatibility with the Raspberry Pi microprocessor used in the vehicle, which will be discussed in the next section. The Raspberry Pi camera offers the fastest performance (30 frames per second) and highest resolution (5MP stills, 1080p video) of any low cost camera for the Raspberry Pi. Its small form factor also makes it ideal for the size constraints of the vehicle.

Additional Sensors

While the SEATURTLE only has 4 sensors built in, others were considered. The main sensor that is found in most other AUVs is a sonar module for underwater mapping and object detection. A sonar system was not included in the first prototype due to the size and cost of most commercially available underwater sonar modules. However, in future iterations of the vehicle, a sonar package as well as additional sensors can easily be added.

Processing

Unlike remotely operated vehicles, an AUV has to be able to “think” for itself. This “thinking” usually involves gathering data from sensors, processing the data, and then using it to act in some manner. This can be done using either a microcontroller, or a microprocessor. Microcontrollers generally have less computational power but are better at interfacing with sensors than microprocessors. For this project the following microcontrollers/microprocessors were considered:

	Cost	Processor Speed	GPIO	Communication	Misc
Arduino Due	$50	84MHz	54 GPIO, 12 PWM, 12 analog	SPI, UART, USB	2 ADCs
Mbed LPC1768	$55	100Mhz	30 GPIO, PWM, analog	Ethernet, USB, I^{2}C, UART, SPI	ADC
Raspberry Pi B+	$40	700Mhz	27 GPIO	Ethernet, UART, USB, I^{2}C, SPI, HDMI	Camera Port
Beaglebone Black	$45	1Ghz	2x46 GPIO, PWM	USB, Ethernet, HDMI	

Table 3: Microcontroller/Microprocessor Comparison

Of the available hardware the Arduino and Mbed provide the best interface for the sensors and motor control, however they are not powerful enough to operate the camera and process the images. Between the Raspberry Pi and Beaglebone the Beaglebone is more powerful but the Raspberry Pi has a much longer track record of success in similar robotics projects. The Raspberry Pi also has a purpose built camera module for use with image processing tasks. For these reasons the Raspberry Pi B+ was selected for the prototype of this vehicle.

The Raspberry Pi is able to communicate with the IMU and Pressure sensor through its I^{2}C interface. The output of the encoder is read using one of the GPIO pins. Control of the motor drivers is also done through the GPIO pins. One limitation of the Raspberry Pi is a lack of built in PWM support. As mentioned earlier the motor drivers are able to vary the speeds of the motors by using PWM to control the total amount of power going to the motors. Despite the lack of hardware support, this speed control can still be accomplished using the Raspberry Pi, by using the built in software PWM capabilities. While not as accurate as hardware PWM, the software package allows any of the GPIO pins to output a PWM signal that is more than sufficient for varying the speeds of the motors.

In addition to interfacing with the other systems in the vehicle, the microprocessor also has to be able to communicate with other computers. By adding a USB Wi-Fi dongle to the Raspberry Pi it is able to generate an ad-hoc Wi-Fi network. Users can then log onto this network to control the vehicle remotely and transfer data. Since the communication is done wirelessly there is no need for any ports on the vehicle, which reduces the potential for leaks. Additionally, by generating its own network the vehicle does not need a Wi-Fi router or Internet connection in order to communicate with other systems. This is very important since it will often be deployed from boats that do not have an Internet connection. Unfortunately this wireless communication does drop out almost immediately after the submarine dives below the surface, but by not having to be constantly tethered to the surface the vehicle's range and maneuverability are greatly improved, and assuming the autonomous behavior is programmed correctly, the vehicle will safely return to the surface to transmit data after its mission is complete.

Electronics

The motor drivers, sensors, and microprocessor discussed so far make up the key components of the vehicles electronics system. In order for all of these components to properly operate they need additional circuitry. The full electronics schematic is broken into parts and discussed below. For the final prototype a custom printed circuit board (PCB) was designed. The PCB reduces the overall size of the circuitry, and makes the system much more robust. A complete schematic and drawing can be found in the appendix.

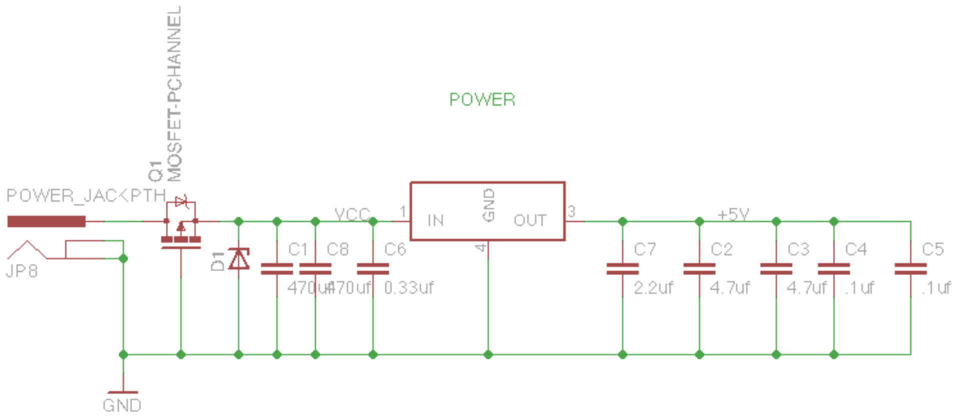

Figure 7: Power supply circuit

In order for the system to operate it needs a power supply. Power is supplied by a 7.4V lithium polymer battery pack. The power supply circuitry takes this 7.4V supply as an input and produces a regulated 5V output. This regulated 5V is used to power the Raspberry Pi, IMU, encoder, and motor drivers. The Raspberry Pi includes a second voltage regulator to generate a 3.3V supply that is used for the pressure sensor. In addition to the voltage regulator, the circuit contains two 0.47uF and two 0.1uF capacitors to smooth any ripples in the voltage levels. When motors turn on they draw a disproportionally high start up current, in order to prevent this from affecting the rest of the circuitry two 470uF reservoir capacitors are included to provide extra current during motor startup. To protect the system from a voltage spike, a zener diode is placed between the input line and ground, which will short any high voltage to ground and prevent it from damaging any of the other components. Additionally, to protect the system from a reversed polarity, i.e. plugging the battery in backwards, a PMOS FET is installed between the supply line and ground. This FET is installed backwards from its normal orientation, such that if there is a higher voltage at ground than the supply line, the FET will shut off and no current will pass through it, protecting the rest of the circuit.

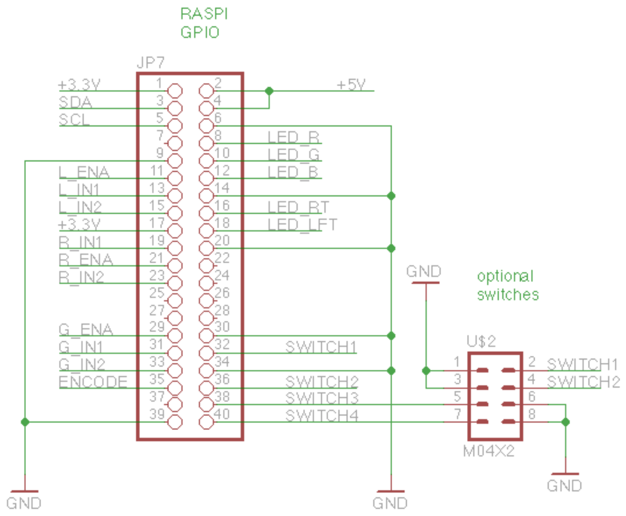

Figure 8: Raspberry Pi interface

The circuit board connects to the Raspberry Pi through its 40-pin header. The Raspberry Pi is powered through the header using the regulated 5V supply. The header also provides access to all of the GPIO pins and I^2C communication interface that is used to communicate with the vehicles sensors. In addition a set of 4 switches have been added. These can be programmed by the user to control a variety of functions including turning Wi-Fi on or off, starting missions, and controlling the headlights, to name a few. All of the unused pins are left exposed and available for future additions to the system.

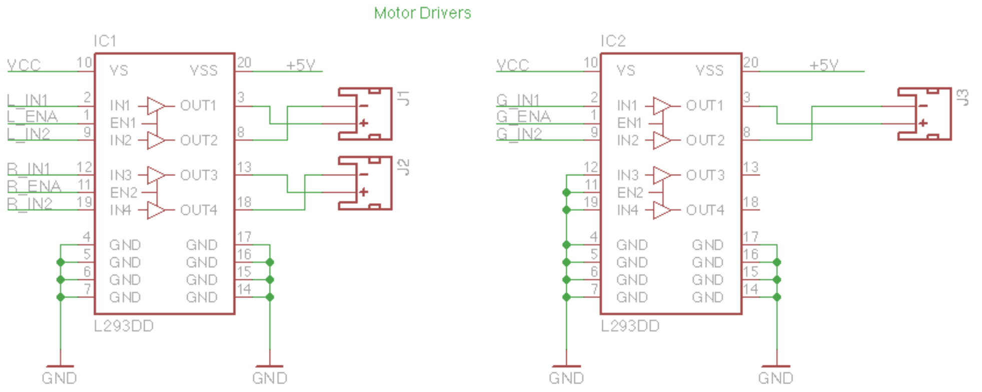

Figure 9: Motor drivers

Two of the L293D motor drivers described in the propulsion section are included on the board to control the two thrusters as well as the gear motor. The drivers are powered from the boards regulated power supply and controlled using the Raspberry Pi's GPIO pins. The power from the motors comes directly from the battery pack, as they require more current than the regulator can safely output.

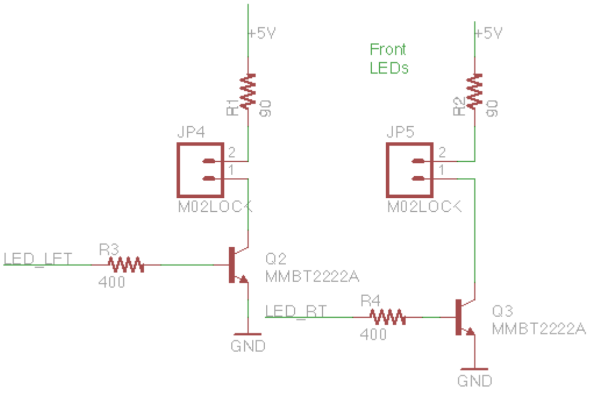

Figure 10: Headlights

In order to provide illumination underwater two ultra-bright LED headlights are included. The LEDs are connected to NPN transistors that allow the low power GPIO pins of the Raspberry Pi to turn the headlights on and off. These headlights were not installed in the first prototype of the vehicle because it will only be operating in well-lit environments, but they can easily be installed on future iterations.

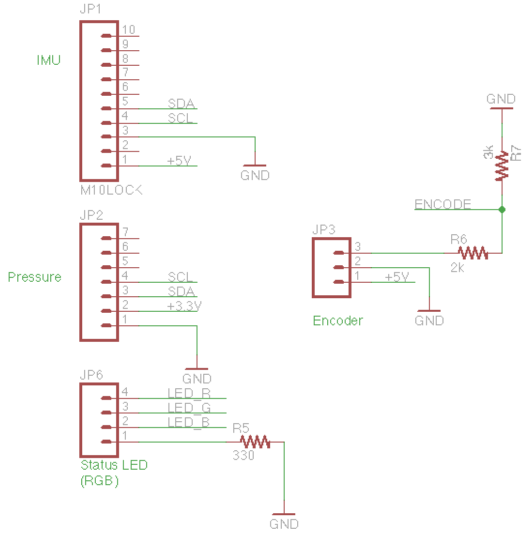

Figure 11: Sensor interface and signal conditioning

The circuit board provides an interface for all of the vehicle's sensors. These connectors provide power to the sensors and enable communication between the sensors and the Raspberry Pi. The output signal of the encoder is a 0 to 5V square wave, however the Raspberry Pi can only safely handle 3.3V inputs. Therefore a voltage divider was added to the encoder output signal to lower its peak from 5V to 3V.

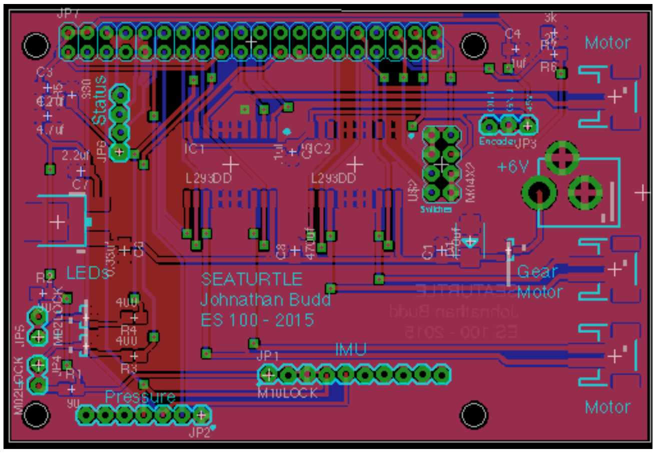

Figure 12: Printed Circuit Board (PCB) layout

The circuit board layout was done using EAGLE. The board is 85cm x 56cm, matching the dimensions on the Raspberry Pi, with the 40-pin header placed to align the board on top of the Raspberry Pi. The battery connection is a 3.5mm barrel plug, chosen because it will not allow the battery to be plugged in backwards, preventing potential damage to the electronics. The JST connectors used for the motors are also mono-directional to ensure that the motors will always spin the same direction. The board has two signal layers, with all of the components placed on the top layer. The power and motor traces are thicker than the data signals on the board, in order to handle a higher current load. Gerber files for fabrication were generated using the Sparkfun CAM files[18] and EuroCircuits fabricated the board.

Computer Vision

Commonly, animals involved in research are tagged for tracking. These tags can range from simple colors and numbers to advanced radio transmitters. To keep the cost and complexity of the system low, tracking will be done using a passive tag, i.e. a tag that does not require its own power source. A research team will need to be able to keep track of and distinguish between multiple tagged objects so the tags have to have uniquely identifiable features. If humans are performing the monitoring this can easily be done with numbered tags, however it is much harder for computers to distinguish numbers. Computer vision has however, advanced to a point where patterns are relatively easy to recognize and distinguish. In addition to these requirements the tag must also be recognizable underwater. This presents a challenge because light does not penetrate water as well as air, and certain colors such as red and orange only penetrate the first few meters of the ocean[19]; therefore tags utilizing differences in color will not be effective underwater.

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[18] (Sparkfun n.d.)

[19] (Ocean Explorer n.d.)

Figure 13: April Tag[20]

Rather than trying to develop a complete tag and recognition system from scratch, existing open source solutions were examined. The April Tag system developed by Ed Olsen at the University of Michigan[21] uses square tags with patterns of black and white squares that the software can use to calculate the exact position and orientation of the tag relative to the camera. There are 5 families of tags, each with approximately 30 different tags, all of which are uniquely identifiable. Since the recognition is based on contrast rather than color the tags are far more likely to work underwater, however no prior usage of the tags underwater could be found. To determine if these tags could be a viable system, several were printed and laminated and placed underwater. Video was taken using a GoPro camera in an underwater housing. This video was then processed using the April Tag software, which was able to successfully identify the tags underwater.

Housing

All of the systems described thus far, with the exception of the tags and thrusters, have a severe aversion to water and will almost certainly catastrophically fail if exposed to excessive moisture. Therefore, it is crucial that the vehicle have a properly designed waterproof housing. The housing must be waterproof to at least 10m per the project specification. It must also provide access to all of the components to allow for repairs, charging batteries, design modifications, etc. The two solutions considered to meet these requirements are metal and plastic piping.

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[20] (April Robotics Laboratory n.d.)

[21] (April Robotics Laboratory n.d.)

Pipes have threaded fittings that can easily be assembled into a torpedo shaped housing, and they are designed to carry pressurized water and gas without leaks. Between metal and plastic pipes, metal is stronger, but PVC plastic is much cheaper and easier to work with. In regards to depth resistance, 3” PVC pipe has a rated operating pressure of 158 psi[22], equivalent to 110m (11atm) below the surface, far beyond the 10m target depth for this vehicle.

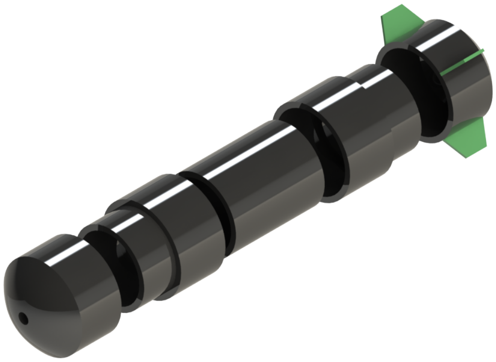

Figure 14: Housing

The housing is 12” (30cm) long and 4”(10cm) in diameter, with a 3”(7.5cm) internal cavity to hold the components. Both the forward and rear caps can be unscrewed to provide access to the internal components. While fluid dynamic modeling and hull design is outside the scope of this project, the shape was chosen to resemble a torpedo to minimize drag in the water. A set of four fins at the rear of the housing provides stability as it moves through the water.

Software

In order to successfully track objects, and perform other missions, the vehicle must be programmed to carry out a set of basic tasks. These functions can then be combined and built upon to create more complex behaviors. Any movement of the

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[22] (Engineering Toolbox n.d.)

vehicle requires at least one of the three motors. Therefore, turning on the motors is among the most basic functions of the vehicle. In order to set the motor speed, the corresponding enable pin on the motor controller is initialized as a software PWM channel with a frequency of 500hz, and the duty cycle is varied from 0 to 100% based on the desired speed. The direction of the motor is controlled by setting the two corresponding input pins of the motor controllers to either (high, low) or (low, high). When combined with feedback from the sensors, these functions can be used to set the rotation of the thruster pods, move in a straight line, turn, or perform any other maneuvers a user can think of. The vehicle also has functions for retrieving and processing data from all of the sensors. These functions serve as a layer of abstraction between the hardware and software, making it easier for developers to program complex behaviors for the vehicle. This is in line with the overall project goal of creating a robust hardware platform that can be programmed to carry out a variety of tasks by different users. The entire codebase for the vehicle is publicly accessible on github[23] for use in future applications.

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[23] (Budd n.d.)

Fabrication and Integration

The previous chapter outlines the major components of the vehicle and the decisions that went into their design and selection. This next section will focus on how these systems were fabricated and integrated into a single functioning vehicle. All of the parts can be separated into three groups, the internal components that must be protected from water, the external components that come into contact with water, and the components that interface between the internal and external environments.

To provide easy access to the internal components, they are all mounted to a single laser cut acrylic plate that can be entirely removed from the housing. This plate is then screwed into the housing to prevent anything from moving, regardless of the orientation of the vehicle.

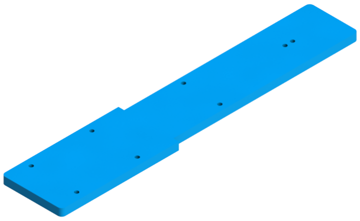

Figure 15: Acrylic mounting plate

To prevent the vehicle from constantly floating to the surface ballast has to be added to keep it close to neutrally buoyant. The total volume of the vehicle measured by submersion is 2600cm^3; therefore in order to match the density of water and be neutrally buoyant it must weigh 2600g. Without any ballast the entire vehicle has a mass of 1900g. The additional 700g were added using 5 pieces of brass.

Component	Mass
Housing + Thruster Pods	1545g
Internal Components w/o batteries	280g
Batteries	75g
Brass Ballast	700g
Total	2600g

Table 4: Mass of components

The right angle gearbox and motor are mounted on the base plate such that the output shaft of the gearbox is located in the center of the submarine, lengthwise and height wise. This was done to ensure the thrust from the motor pods does not push the submarine off balance while moving forward, or during depth changes, with the pods rotated up or down. The optical encoder is also attached to this output shaft to measure rotation of the pods.

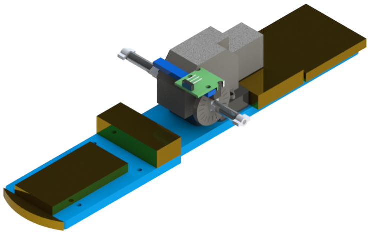

Figure 16: Mounting plate with ballast, gearbox, and encoder

The gearbox has to be able to rotate the pods while the vehicle is operating, but it also has to be able to slide out of the body attached to the base plate. To enable this functionality, an interlocking joint (Figure 17) was designed.

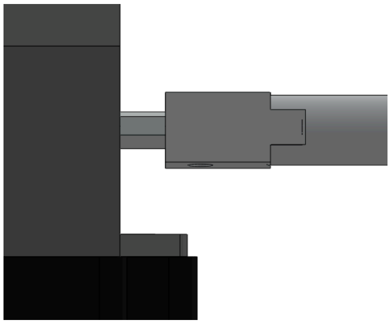

Figure 17: Interlocking thruster rotation joint

When the base plate is secured to the housing the adapter on the end of the gearbox shaft is aligned with the slot in the shaft attached to the motor, allowing for the transfer of torque from the gearbox to the motor pods.

In order to secure the two main thrusters outside the housing, a mount had to be fabricated that could hold the base of the thrusters in place, while connecting the rotating portion of the thruster to the gearbox inside the hub. After testing with a 3D printed prototype the final set of mounts were machined out of aluminum, which was chosen for its corrosion resistance.

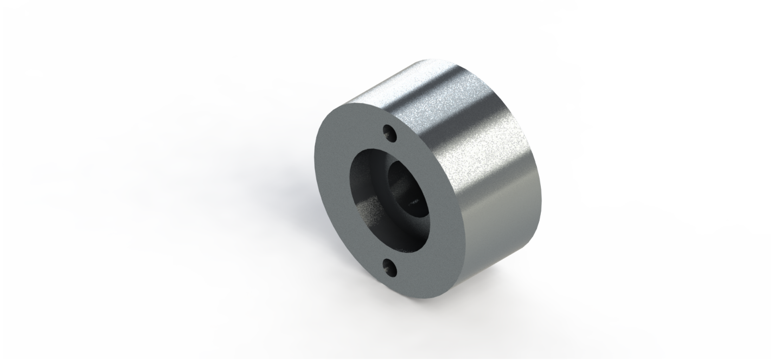

Figure 18: Motor mount

An aluminum shaft and acrylic adapter connect the rotating portion of the thruster to the gearbox. If too much torque is applied to the thruster, the acrylic adapter will break, preventing any permanent damage to the gearbox or thruster. To prevent water from entering the housing an O–ring is placed between the base of the thruster and the mount. The adapter shaft attached to the gearbox rotates inside a lip seal, as an added barrier of protection. A laser cut stainless steel backing plate holds the lip seal in place.

Figure 19: Motor mount exploded view. From left to right: aluminum shaft, backing plate, lip seal, motor mount, acrylic adapter, O-ring, thruster

It is important that all of the critical electronic components are securely mounted to prevent them from being damaged. In addition, since this vehicle operates underwater the electronics need to be as isolated as possible in the event of a leak. To accomplish this the Raspberry Pi is mounted to an acrylic plate that is held 0.25" above the main baseplate of the submarine. The custom PCB attaches directly on top of the Raspberry Pi and the camera is fastened to an acyclic plate that is solvent welded to the Raspberry Pi's base plate. An acrylic bulkhead is placed in between these electronics and the rear compartment of the vehicle that houses the gear motor and batteries. The bulkhead has an O-ring around its perimeter that creates a seal with the inner wall of the housing. While not suited for stopping major leaks the bulkhead will keep small amounts of water isolated in the back of the submarine. If any water does leak into the front compartment, all of the electronics are at least 0.5" above the bottom of the vehicle, which will protect them for a short time. The battery pack attaches to the rear of the base plate with Velcro so it can easily be removed for recharging.

The pressure sensor is the only internal electronic component that is permanently affixed to the housing. In order to allow the top of the sensor to come into contact with the external water pressure, and still have the back of the sensor accessible for transferring data, the sensor is permanently glued inside the housing. To allow water to come into contact with a sensor a small hole was drilled in the housing.

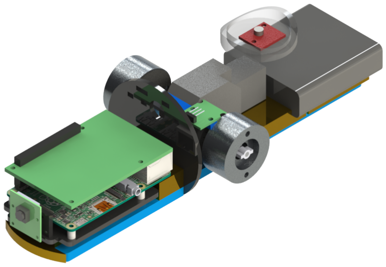

Figure 20: Mounting plate with gearbox, ballast, electronics, sensors, bulkhead, and battery

The housing is assembled from two 3” PVC male threaded adapters attached to either end of a 4.5” long piece of 3” pipe using PVC cement. The ends are sealed using two 3” female threaded end caps. A CNC mill was used to cut a 1.5” diameter hole through the center of the housing, into which the aluminum motor mounts were epoxied. The entire housing was polished to remove leftover imperfections from the manufacturing process and then spray-painted. Four laser cut acrylic fins are attached to the rear end cap using epoxy. A 0.75” diameter hole was cut in the front end cap, and filled in with a piece of clear acrylic and sealed with epoxy. This window allows the camera mounted inside the body to safely capture images. The wiring for the motor pods is run through two holes drilled in the top of the housing. The space around the wires is sealed using epoxy. In this first prototype of the vehicle the motor pods are permanently attached to the housing by their wires due to a lack of appropriately sized and priced underwater connectors. This will be changed for future versions of the vehicle.

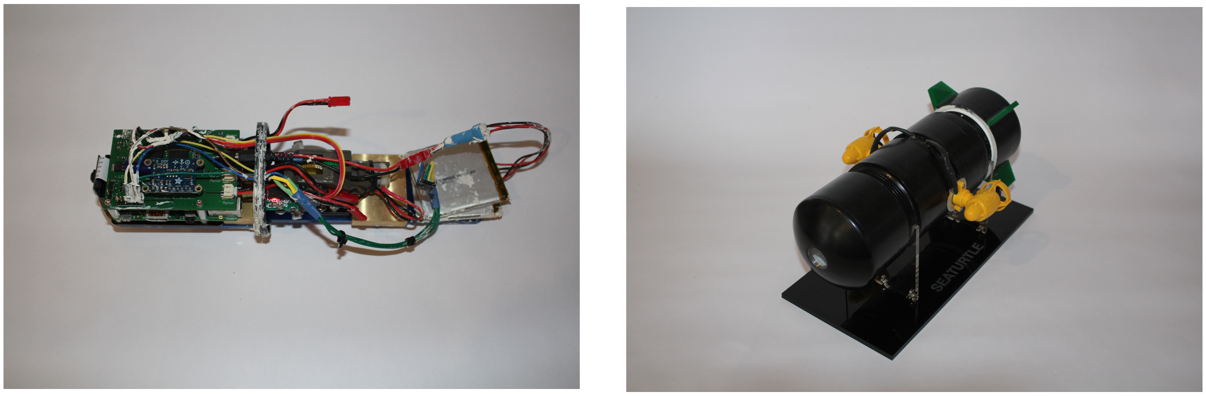

Figure 21: (left) Assembled mounting plate, (right) fully assembled vehicle

Testing and Analysis

Among the most important parts of any project is the testing and analysis of the design and fabrication. This chapter will detail the tests conducted on, and with the SEATURTLE, and analyze the results. Testing and analysis was broken up into the following parts:

- Buoyancy/Depth
- Propulsion
- Velocity
- Depth Control
- Operating Time
- Camera/Tag Detection
- Autonomous Tracking

Buoyancy/Depth

In order to minimize the amount of energy required to maintain a certain depth the vehicle needs to be as close to neutrally buoyant as possible, so that it neither sinks nor floats. As discussed in the fabrication chapter this was accomplished by adding brass ballast to the vehicle. It is also important that the weight of the submarine be evenly distributed along its length so that it sits in the water evenly. In order to properly balance the distribution of weight, the forward and rear portions of the vehicle were placed on separate scales. Weight was then redistributed until both scales showed the same weight, equal to half of the total mass of the vehicle. Submerging the vehicle in water and observing that it neither sinks nor floats, and that it sits level in the water confirmed, the amount and distribution of ballast. Small adjustments can be made by adding and or removing weight as necessary. While it is important that the weight of the submarine is equally distributed along its length, it is also important that the majority of the weight sit at the bottom of the vehicle, to prevent it from turning upside down. It is also important to note that buoyancy calibration was performed in fresh water with a density of $1 g/cm^3$. When the vehicle is used in saltwater, more ballast will have to be added, as saltwater is denser than fresh water.

Of all the design specifications, having a waterproof housing is among the most important. If the housing cannot keep water from coming into contact with the electronics, all of the other systems will cease to operate. The ideal method for testing the vehicle at a depth of 10m, per the design specifications, would be to submerge it 10m below the surface and see if any water gets inside. Due a lack of incredibly deep tanks the depth has to be simulated. This can be done in two ways, either by placing the vehicle in a shallow tank of water and increasing the air pressure in the tank, or pressurizing the inside of the housing and seeing if any air escapes. The first option is almost identical to actually submerging the vehicle to a given depth, but this also requires a pressure tank large enough for the vehicle in order to be tested safely, something that is unavailable for this project. Pressurizing the inside of the housing is much easier to accomplish, although it is slightly less accurate. When the vehicle is submerged it will be experiencing higher external pressures trying to force water inside. Using air to pressurize the inside of the vehicle can create the same pressure differential, but the seals will now be working in the opposite direction. For this prototype this test is sufficient, as all of the seals are simple threads and O-rings that perform equally well in both directions. Additionally, since air molecules are much smaller than water, if the seals are able to prevent air from escaping, they will be sufficient to keep water out.

Figure 22: (left) Vehicle attached to air compressor, (right) Vehicle submerged to detect any air escaping

In order to pressurize the housing the normal front end cap was replaced with an identical PVC end cap with the addition of an attachment point for an air compressor. In order to ensure a tight seal at the threaded joints they were first wrapped in Teflon plumbing tape and then coated with Teflon paste and hand tightened. The air compressor was used to create the pressure differential across the housing. The housing was then submerged in water to identify any air bubbles escaping. The pressure inside the housing was repeatedly increased to 17psi, which is the equivalent pressure the vehicle will experience 12m (1.2atm) below the surface, without any air leaking. For safety reasons the housing was not tested to failure, but this testing shows the vehicle can safely operate without leaking at the target depth of 10m.

Propulsion

In order to conduct almost any underwater mission the vehicle has to be able to move in a straight path. For this to occur the motors must output equal amounts of thrust. Due to inherent differences in manufacturing and uneven wear between the motors, this is not the case. In order to characterize how well the submarine can hold a straight course, a test fixture was built that prevents the vehicle from moving forward, while still allowing it to freely rotate. This platform is submerged in a small tank and any imbalance in thrust will cause the vehicle to rotate.

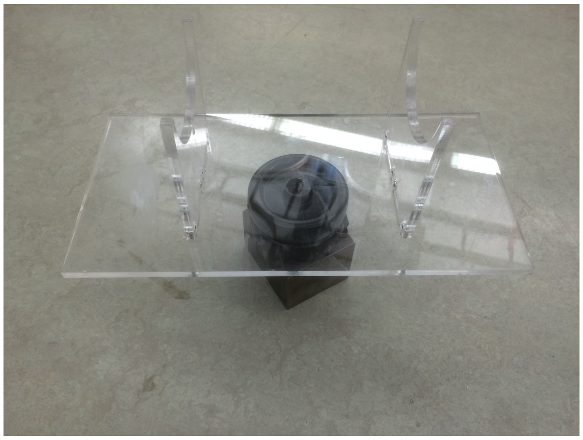

Figure 23: Test platform for steering measurements

The degree to which the vehicle rotates from the desired coursed can be recorded using the gyroscope, which tracks rotation over time.

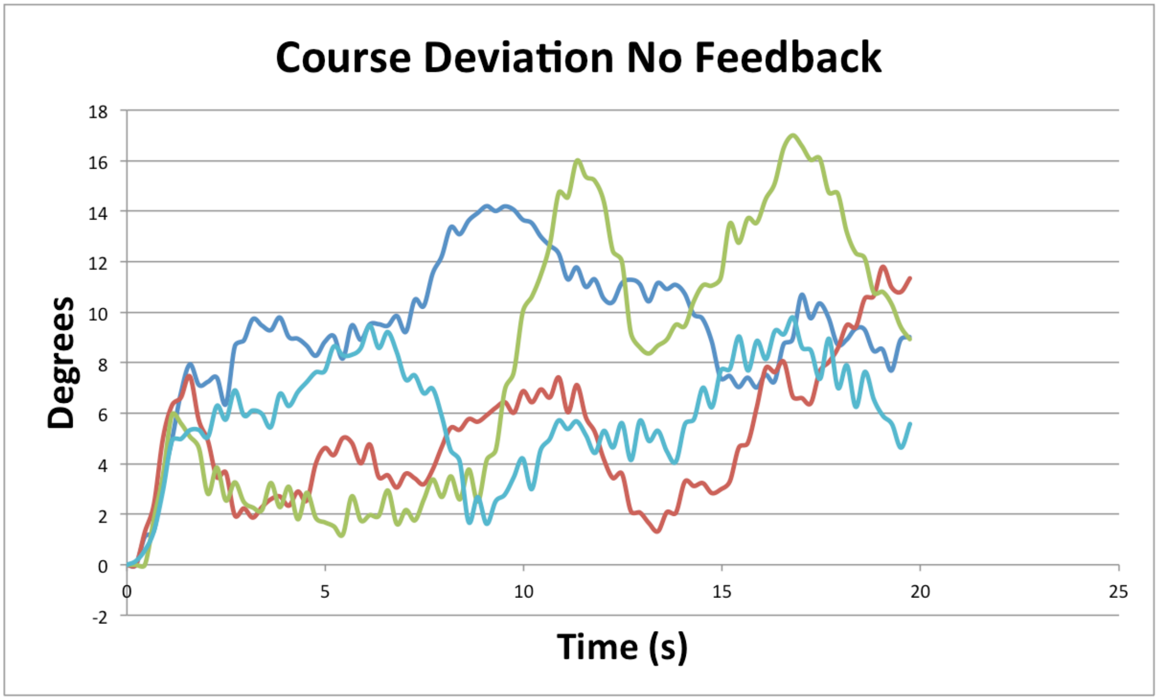

Figure 24: Course deviation with no feedback control for motor speed

Setting both motors to run at the same speed with no feedback results in an extreme deviation from the desired course. Over all trials the vehicle consistently drifts to one side due to one motor delivering more thrust than the other. To account for this deviation motor speed is instead set by incorporating feedback from the gyroscope. Using proportional control, the speeds of the motors are varied in proportion to the number of degrees the vehicle is from the desired course.

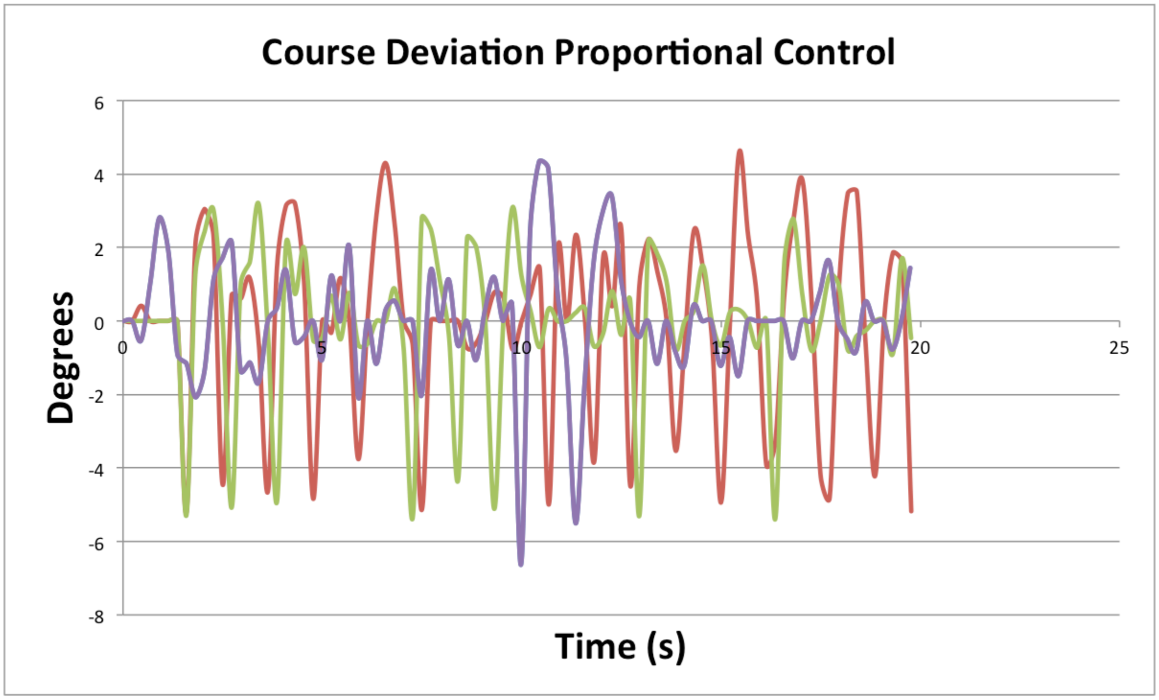

Figure 25: Course deviation with proportional feedback control setting motor speed

Proportional control results in a vast improvement over the vehicle's performance with no feedback, as it is now able to hold a steady course with only minor oscillation. In an attempt to further improve the performance of the system, motor speed is adjusted based on the derivative, or rate of change of the deviation, and the integration or total accumulated deviation, in addition to a fixed proportion of the deviation. This is commonly referred to as PID (Proportional Integral Derivative) control.

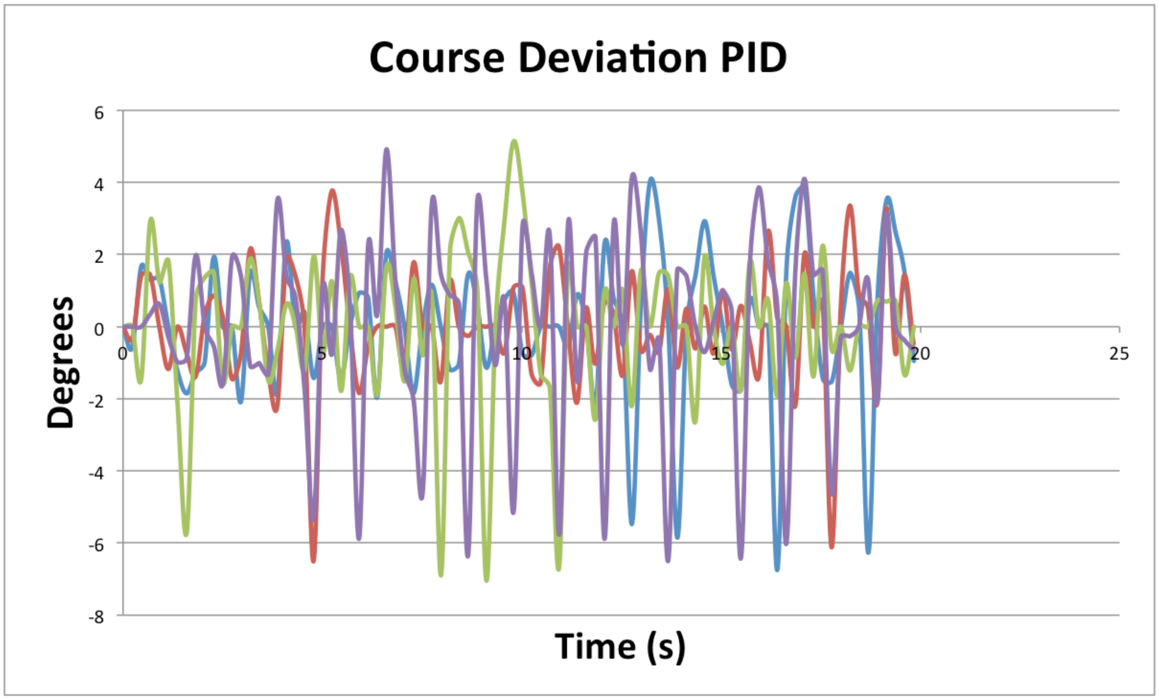

Figure 26: Course deviation with PID control setting motor speed

The oscillation seen in the proportional control is still present but it is now more damped, and the vehicle is able to consistently hold its course for the entire trial.

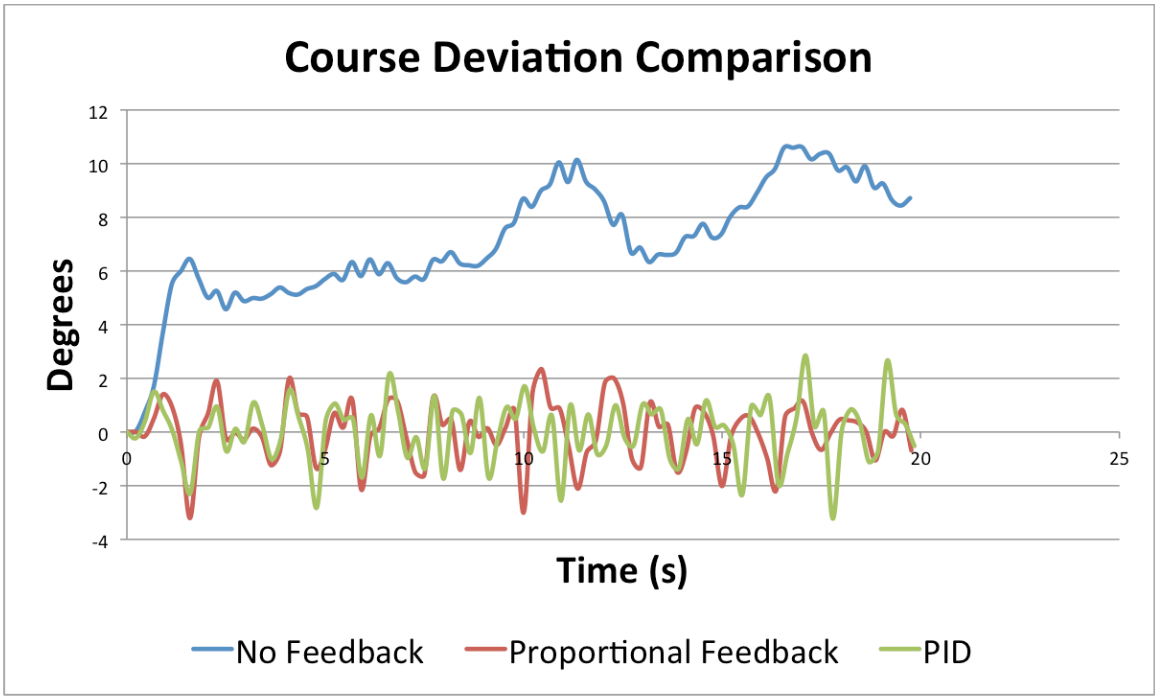

Figure 27: Course deviation comparison

A side-by-side comparison of the average deviation with each control method clearly illustrates the necessity and benefits of using feedback to control motor speed. The total course deviation for each control method can be calculated by integrating the deviation over time.

Control Method	Total Error (degrees)
No Feedback	633.15
Proportional Control	2.11
PID Control	0.07

Table 5: Total course deviation between no feedback, proportional control, and PID control methods for maintaining course

In addition to holding a straight course, the vehicle must also be able to turn precisely. To test the turning radius of the vehicle, it was placed in a small tank and thrust was applied in opposite directions. The vehicle was able to complete a full rotation in a space 8cm wider than its length. While it is unable to turn in place perfectly, as per the design specifications, it does come very close to achieving this goal.

Turning precisely in water presents a unique challenge. While the vehicle is able to sense the number of degrees it has turned using the gyroscope, it is very difficult to stop the vehicle from turning at a precise point, because its momentum causes it to overshoot its target. Applying reverse thrust to slow the turn, such that the vehicle reaches zero angular velocity after turning the desired number of degrees, can prevent this. However, in practice this behavior is very hard to implement. Instead it is much more efficient to constantly update the desired heading of the vehicle and have it always move towards and maintain this heading. As shown earlier the vehicle is very accurate when it comes to maintaining a course and water is much more conducive to gradual change over time than precisely calculated movements.

Velocity

In order to test the top speed of the vehicle it was placed in a pool and driven in a straight line. The time required to move 5m was recorded over multiple trials to get an average velocity of 0.23m/s, just under half the desired speed from the design specifications. While unfortunate this is not unexpected, given that the same thrusters were only able to propel the significantly smaller Swimline RC Submarine at a speed of 0.4m/s. As the vehicle is moving through the water at a constant speed the main force it is experiencing is aerodynamic drag, which is described by equation 1.

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

Equation 1: Aerodynamic drag equation

With all other parameters held constant, doubling the cruising velocity will result in a fourfold increase in the drag force on the vehicle. Therefore, in order to satisfy the design specification for speed, thrusters that are at least four times as powerful will have to be used.

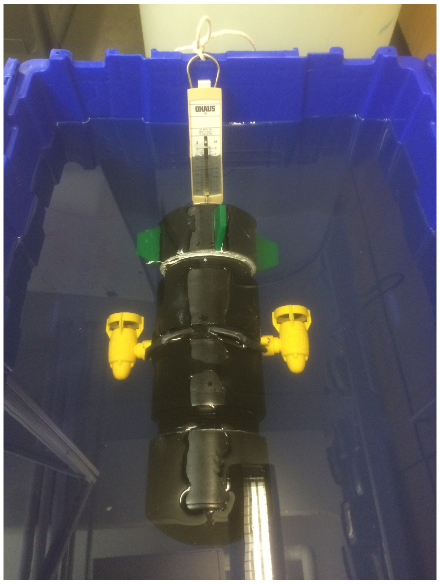

Figure 28: Thrust characterization apparatus

In addition to velocity, the thrust of the vehicle was also characterized. This was done by attaching a spring scale to the back of the vehicle and the side of the testing tank. The vehicle was then driven forward and the maximum pulling force was recorded. With steering feedback to hold a steady course, the maximum thrust is 20 grams. With both motors running at full power, without any feedback for course correction, a maximum thrust of 30 grams was recorded.

Depth Control

In order to determine how well the vehicle can control its depth, it was placed in a pool and driven underwater using the rotating thrusters. The gear motor was able to accurately adjust the tilt of the thrusters, which were able to drive the vehicle between depths. Using feedback from the pressure sensor the vehicle should be able to maintain a set depth, however this proved to be very difficult. While the sensor is able to accurately keep track of the vehicles depth, the motors are not able to respond fast enough. Adjusting the depth requires rotating the thrusters, which is a vey slow process, during which the vehicle continues to change depth. This results in large variations in depth over time.

With further testing the code could be refined to make more gradual changes to the depth of the vehicle, rather than the current strategy of stopping forward motion and fully rotating the pods to adjust depth. However, it would likely be more advantageous to redesign the depth control mechanism to use a system of actively varying the density of the vehicle to dive and surface.

Operating Time

The operating time is dependent on the capacity of the batteries and the power consumption of the systems in the vehicle. Power is supplied by a 7.4V lithium-polymer battery pack, made from wiring two 3.7V cells in series. The pack has a total capacity of 2000mah. To determine the power consumption of the systems in the vehicle, the amount of current drawn by each part was measured. Operating time was calculated using equation 2.

$$\frac{battery\ capacity\ (miliamphours)}{current\ \ (miliamps)} = operating\ time\ (hours)$$

Equation 2: Operating time

With the fully charged 2000mah battery pack, the maximum operating time for the vehicle in different modes of operation are as follows:

System	Current (milliamps)	Operating Time (hours)
Raspberry Pi + Wi-Fi	300	6.67
Image Processing	400	5.00
Full Thrust	1300	1.54
Depth Change	600	3.33
Full thrust + Image Processing + Depth Change	1700	1.17

Table 6: Operating time

The vehicle's design specifications require a minimum operating time of 160 minutes, or 2.67 hours. With the current battery pack this would likely be met, assuming the motors aren't running constantly. If additional operating time is required the size of the battery pack can easily be increased by a factor of 3 or 4, by replacing some of the ballast with additional batteries. This could extend the operating time to over 4 hours with all of the motors running, without adding any extra weight or size to the vehicle.

Camera/Tag Detection

In order to track tagged objects in real time it is important the vehicle be capable of processing images rapidly, and recognizing tags in these images at a significant distance. The maximum distance at which a tag can be detected is determined by both the size of the tag and the resolution of the camera. With the camera above water, at a fixed resolution of 640x480 pixels, the following maximum distances were determined for tags of varying sizes.

Tag size (cm x cm)	Maximum distance (m)
4x4	2
8x8	4
16x16	8

Table 7: Maximum detectable distances fro April Tags of varying sizes

Doubling the length of the sides of the tag corresponds to a doubling of the maximum distance at which the tag can be detected. To test the design specification of detecting a tag at 5m away, a 16cm x 16cm tag was placed underwater at a depth of 1m. The vehicle was able to consistently detect the tag at 7m away, slightly below the values for above water detection, likely due to there being less total light underwater. This does satisfy the requirement of detecting tags 5m away, as a 16cm x 16cm tag is still small enough to attach to an adult sea turtle.

In addition to detecting tags at a distance of 5m, the vehicle also has to be able to process the images quickly. To determine the processing rate a series of 10 images are captured and processed and the total time recorded. The number of images processed is divided by this total time to get the number of frames per second. Using the Raspberry Pi camera and the April Tag processing software, a rate of 0.47 frames per second was achieved. This is far too slow to be considered real time processing.

The slow processing speed of the images is due in part to the limited computation power of the Raspberry Pi, but it is mainly caused by a lack of software compatibility between the Raspberry Pi camera and the April Tags software. The Raspberry Pi camera is purpose built for the Raspberry Pi, which makes it very fast, at the expense of requiring a custom interface. Currently the only stable interface for the camera is written in python, and there is no stable solution for using the camera with C++ and OpenCV. As the majority of the code for the vehicle is written in python this would not be a problem, except the April Tag software is written in C++ using OpenCV functions. Therefore, in order to process an image a python script must first take an image, save it to memory, then call the April Tag software as a sub process, which can then read the image from memory, process the image and return the position of any tags in the image to the python script. The process of writing and reading the image from memory is very slow, and could be vastly improved if the April Tag software were able to take an image directly and process it without ever permanently storing the image. This will be possible once the OpenCV and C++ libraries used in the April Tag software support the Raspberry Pi camera. This is an active area of work in the Raspberry Pi community and several unstable solutions have been published, so it is only a matter of time until the software is able to fully utilize the available hardware.

While the software is currently limiting the speed at which the vehicle is able to process images, it is possible to determine how fast it will be able to operate once the software improves. This can be done by pre-loading video into the April Tag software and processing it, bypassing the time-consuming memory operations. This resulted in a processing rate of 1.44 frames per second, more than 3 times the speed of the current solution.

To further improve the processing speed, the total size of the images being processed can also be reduced. In order to determine the minimum picture size necessary to maintain the 8m above water, 7m below water detection range observed earlier, a 16cm x 16cm tag was placed 8m away and the image size was gradually reduced until it could no longer consistently detect the tag. The smallest image that can be used for consistent detection is 400x400 pixels. The reduced image size had negligible impact on the processing speed using the Raspberry Pi camera due to the previously discussed software incompatibilities. Loading video taken with the reduced resolution directly into the April Tag software resulted in a processing speed of 1.81 frames per second, 26% faster than processing speed for 640x480 images, and a 285% increase over using the Raspberry Pi Camera in its current state.

Autonomous Tracking

The SEATURTLE vehicle is designed to be easily adaptable to a wide variety of missions, depending on the needs of the user. This first vehicle has been optimized to autonomously track tagged objects using image recognition. The autonomous tracking behavior was programmed as a finite state machine, illustrated in Figure 29.

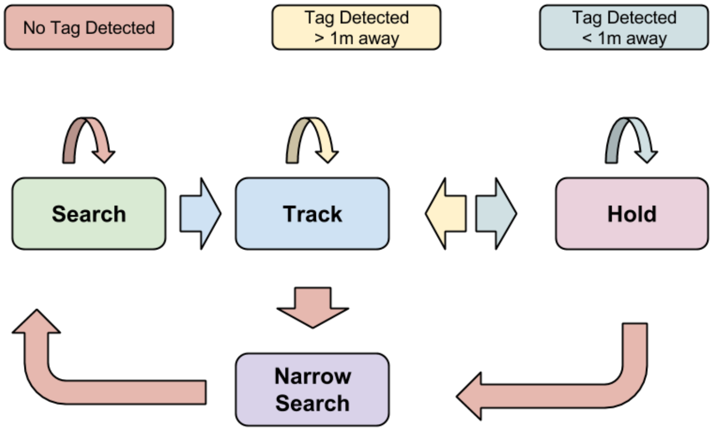

Figure 29: Autonomous tracking algorithm

The default state of the vehicle is search, in which the vehicle rotates in place, taking and processing images. If a tag is detected the vehicle enters the track state, in which it moves towards the tag, adjusting its position to keep the tag centered in its field of view. When the vehicle reaches a distance of 1m from the tag it enters the hold position state. The vehicle will remain in place and in this state until the tag moves. If the vehicle loses the tag at any point during the track or hold positions states, the vehicle does not immediately return to the default search behavior; instead it enters a modified search state that first searches 30 degrees on either side of the vehicle. If this modified search does not recover the tag the vehicle returns to the normal search state and resumes its search for tags.

Testing of the search algorithm was performed in a short course swimming pool. A laminated tag was submerged at distances varying from 1m to 5m away from the vehicle. The simple search algorithm was able to consistently locate and navigate to tags placed at all of these distances, independent of the initial orientation of the vehicle and tag. The algorithm was also able to correct for slight movement in the tag, however due to the slow processing speed of the camera, any rapid movements forced the vehicle to perform a new search to relocate the tag.

While simple, this algorithm was able to demonstrate that the vehicle is capable of autonomously tracking tagged objects underwater. Further improvements to the camera software will result in the ability to process images faster, and therefore track tags much faster. This will allow for more advanced tracking algorithms to be implemented using the existing hardware.

Conclusion

Summary

In order to better understand and learn more about Earth's vast oceans, researchers, scientists, and explorers need a wide array of tools. There are currently few low cost solutions for performing research in shallow aquatic environments. The SEATURTLE project aims to change that, by creating a low cost autonomous underwater vehicle for conducing missions in shallow reef environments. In order to meet this goal the following series of requirements had to be met.

Minimum Depth	1atm = 10m
Maximum Size	3000cm^3
Minimum Speed	0.5m/s = 1 knot
Steering	Zero Drift
Turning Radius	Zero
Tag Identification Distance	5m
Minimum Operating Time	160 min
Maximum Cost	$500

Table 8: Design Specifications

Testing and analysis of the vehicle resulted in a maximum depth of at least 12m (1.2atm), and a total vehicle volume of 2600cm^3. The vehicle is able to steer and hold a course without drifting, and can turn with a near zero turning radius. Depending on the size of the battery pack, the vehicle can easily exceed 160 minutes of operating time. The total cost to build the vehicle is $463, which is broken down in a detailed budget in the appendix. The two main factors that are preventing the vehicle from hitting all of the design specifications are the speed of the vehicle and Tag Identification. The vehicle was only able to achieve a maximum speed of 0.23m/s, which is less than half the target speed. While unfortunate this was expected, due to the poor quality of the thrusters and a lack of a cost effective commercially available alternative. The vehicle is able to consistently detect tags underwater at distances greater than 5m, satisfying the design specification, but the slow processing rate limits performance of object tracking. The processing speed can be more than doubled once the camera is able to properly interface with the software. While designing the vehicle with a different camera would have provided for faster image processing in the short term, the Raspberry Pi camera hardware is still the best available for this application, and with future software updates will provide the best performance as well. Additionally, the recently announced Raspberry Pi 2, with 6 times the speed and double the memory, yet the same cost and form factor as the Raspberry Pi B+ currently used in the vehicle, will significantly increase performance in future iterations of the vehicle, without requiring any changes to be made to the design.

Before this vehicle can be used to conduct field research, the potential regulations must be considered. Due to its small size the vehicle does not meet the 5-ton displacement threshold for US Coast Guard registration. There are currently no specific regulations for the operation of autonomous underwater vehicles, although this may change as they become more popular. The Department of Defense regulates the exportation of AUVs with military applications, but as a research vessel the vehicle is exempt. The only regulations that currently need to be considered are in regards to the transportation of Lithium Polymer batteries. The US Department of Transportation regulations[24] can be referenced for proper shipping and handling of the batteries used in this vehicle.

This project began with the goal of creating a low cost tool for autonomously tracking tagged objects underwater, and this goal has been met. The first iteration of the vehicle does not move or think as fast as initially desired, but it works nonetheless. The vehicle is capable of both reducing the cost and improving the quality of oceanic research.

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[24] (US Department of Transportation n.d.)

Future Work

The current vehicle serves as a viable proof of concept, however future work can significantly improve its performance in many areas.

Propulsion

The biggest limitation of the current vehicle is its speed. The performance can be greatly improved with a new set of thrusters. Due to a lack of commercially available underwater motor pods, these new thrusters would likely have to be custom designed. New thrusters would likely not require any modifications to the rest of the vehicle as the interface between the housing and the pods can easily accept almost any size motor, and the motor drivers are outputting less than half their rated power to drive the current thrusters.

Depth Control

The current method of depth control, tilting the thrusters up and down, works but it could be greatly improved. A more complicated but better method such as actively pumping water in and out of the vehicle, as is done in real submarines and larger AUVs, would both improve performance, and eliminate the need to have the gearbox and motor to rotate the thrusters. Since the current vehicle is neutrally buoyant, it will not necessarily return to the surface in the event of power loss. A more robust design would allow the vehicle to default to a positively buoyant state, and float to the surface if power is lost for any reason.

Image Processing

Improving the interface between the camera and image processing software is essential, however this will only improve processing speed to just under 2 frames per second. In order to further improve performance of the vehicle different tag options should be considered. The April Tag software is computationally intensive and could be modified to provide less information, i.e. no roll, pitch data, in order to improve processing speed. The April Tags could also be abandoned altogether in favor of a simpler tag.

Processor

In the short term the Raspberry Pi B+ can be upgraded to the newly released Raspberry Pi 2 without the need for any other changes as they have the identical form factor and interface. Future versions of the vehicle could potentially explore using a smartphone to both take images and handle all of the processing for the vehicle, although the greatest improvements in both performance and size would come from integrating all of the electronics, i.e. processors, motor drivers, sensors, etc., on a single circuit board.

Thermal Management

Currently the vehicle has no way to monitor or regulate its temperature. The PVC housing will trap the majority of the heat generated by the electronics and motors. Future work could look at adding a way to exchange heat with the surrounding water.

Sensors

The current sensor package is adequate for performing a large variety of tasks, but it could be greatly improved with the addition of a sonar module. Sonar would allow the vehicle to map its surroundings, and more safely navigate tight spaces.

Software

Currently the vehicle is being used for the very specific application of tracking tagged objects, but by simply uploading new code, the same hardware can be used for a wide array of tasks.

Collective Behavior

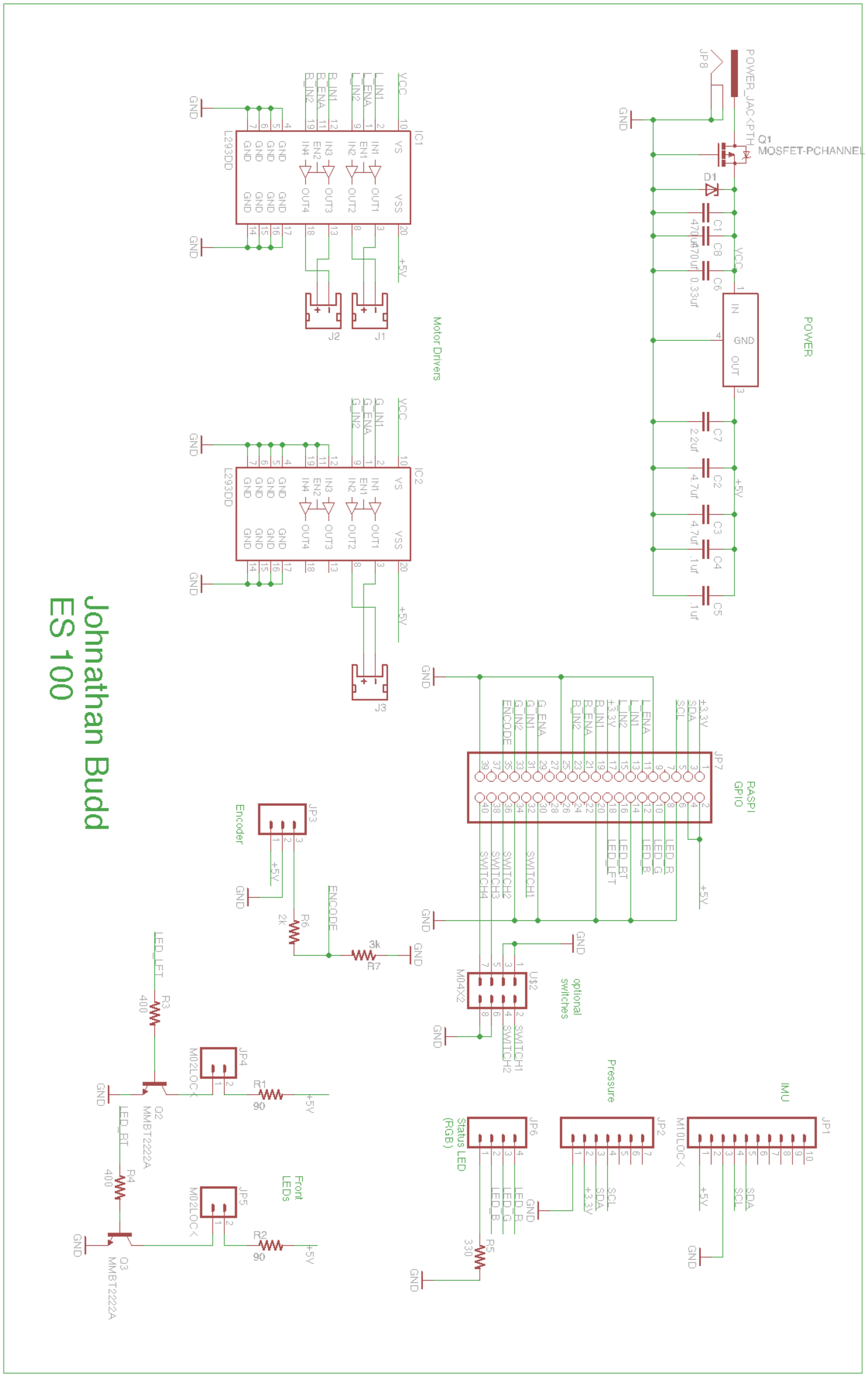
Some of the most exciting ongoing work in robotics involves using groups of simple robots to complete complex tasks. For a relatively low cost an entire swarm of these vehicles could be produced, and programmed to work together.

Commercial Applications

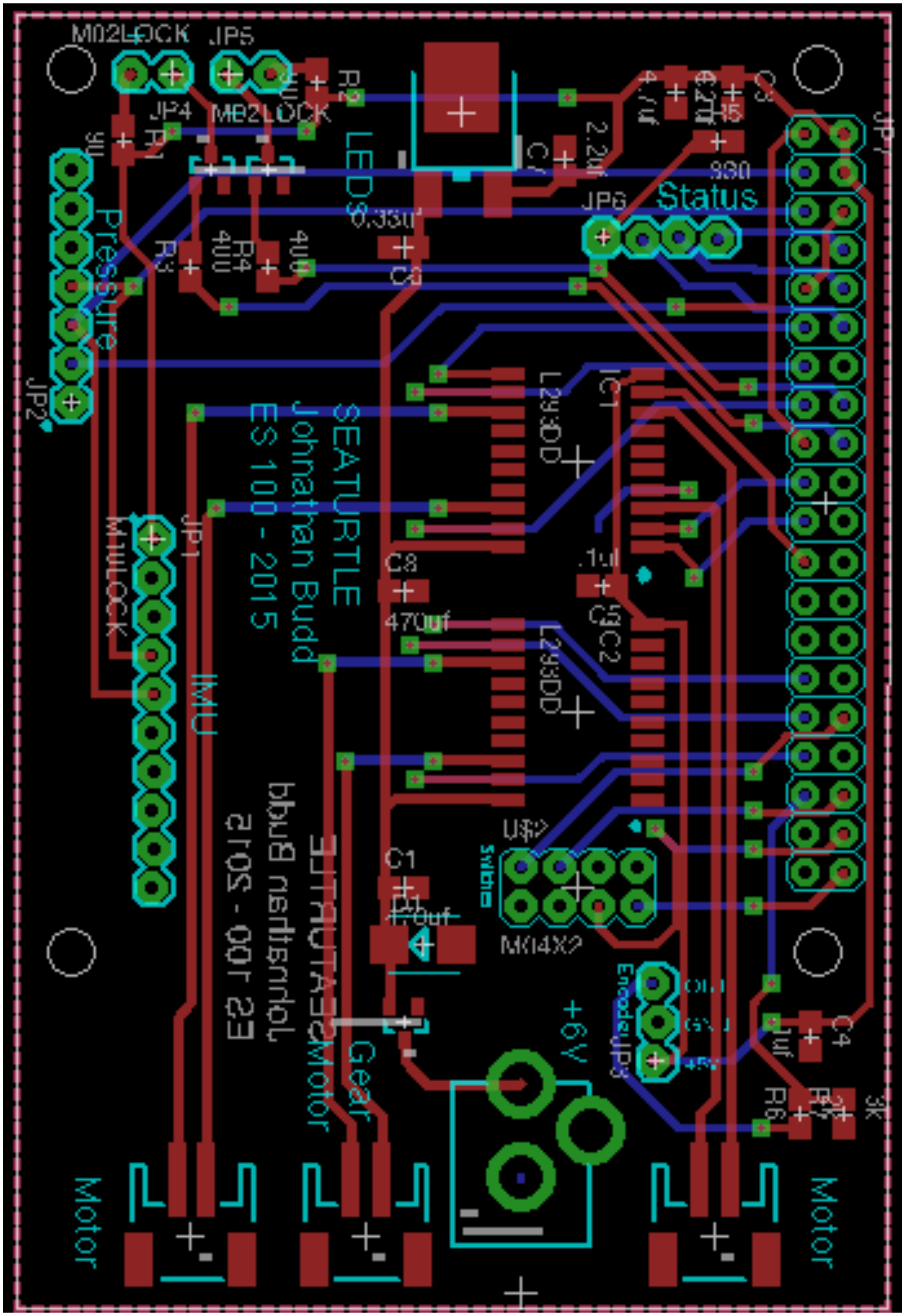
In addition to being used as a research platform the SEATURTLE could be adapted for recreational use. The last few years have seen a tremendous increase in the availability and demand for recreational drones for aerial photography. The SEATURTLE can provide a similar platform for underwater photography. Potential applications include tracking and recording SCUBA divers, or autonomously exploring a reef and capturing video, among many others.

Appendix A: Electronic Schematic and PCB Layout

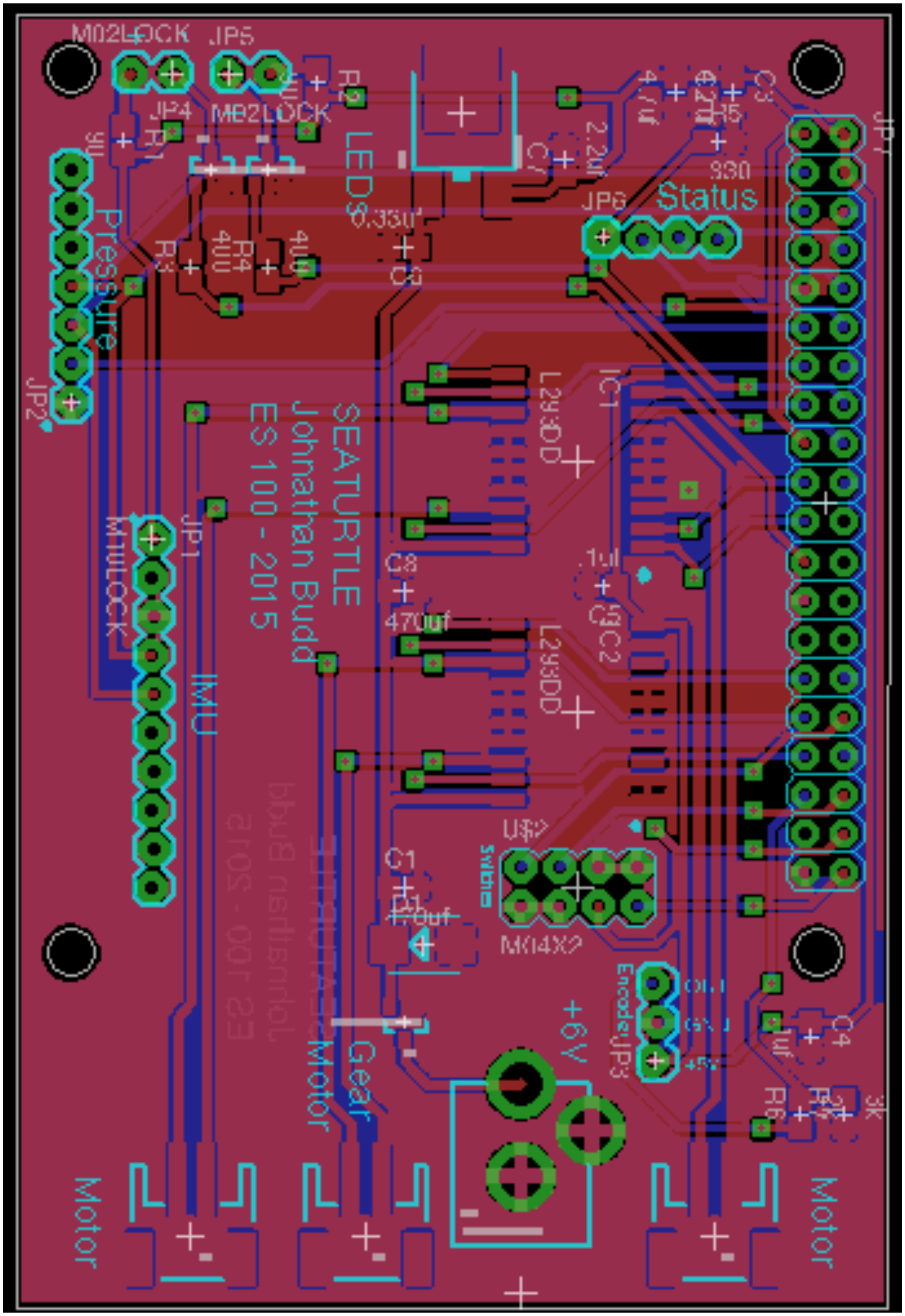
Schematic



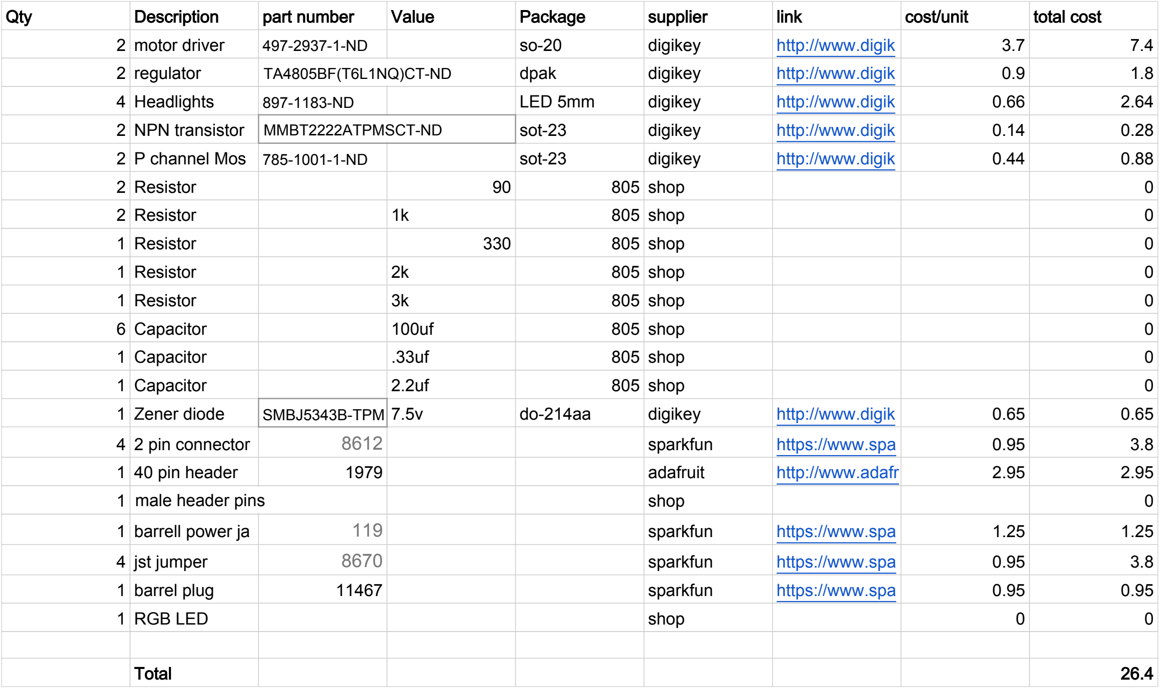
PCB layout without ground plane



PCB layout with ground plane



Circuit Board Bill of Materials



Qty	Description	part number	Value	Package	supplier	link	cost/unit	total cost
2	motor driver	497-2937-1-ND		so-20	digikey	http://www.digik	3.7	7.4
2	regulator	TA4805BF(T6L1NQ)CT-ND		dpak	digikey	http://www.digik	0.9	1.8
4	Headlights	897-1183-ND		LED 5mm	digikey	http://www.digik	0.66	2.64
2	NPN transistor	MMBT2222ATPMSCT-ND		sot-23	digikey	http://www.digik	0.14	0.28
2	P channel Mos	785-1001-1-ND		sot-23	digikey	http://www.digik	0.44	0.88
2	Resistor		90	805	shop			0
2	Resistor		1k	805	shop			0
1	Resistor		330	805	shop			0
1	Resistor		2k	805	shop			0
1	Resistor		3k	805	shop			0
6	Capacitor		100uf	805	shop			0
1	Capacitor		.33uf	805	shop			0
1	Capacitor		2.2uf	805	shop			0
1	Zener diode	SMBJ5343B-TPM	7.5v	do-214aa	digikey	http://www.digik	0.65	0.65
4	2 pin connector	8612			sparkfun	https://www.spa	0.95	3.8
1	40 pin header	1979			adafruit	http://www.adafr	2.95	2.95
1	male header pins				shop			0
1	barrell power ja	119			sparkfun	https://www.spa	1.25	1.25
4	jst jumper	8670			sparkfun	https://www.spa	0.95	3.8
1	barrel plug	11467			sparkfun	https://www.spa	0.95	0.95
1	RGB LED				shop		0	0
	Total							**26.4**

Appendix B: Budget

Item	**Vendor**	**Quantity**	**Unit Cost**	**Total Cost**
submarine	Amazon	1	49.99	49.99
raspberry pi	sparkfun	1	49.95	49.95
IMU	adafruit	1	19.95	19.95
Pressure Sensor	Sparkfun	1	59.95	59.95
parts for PCB fab	digikey	1	26.4	26.4
Pi camera	sparkfun	1	29.95	29.95
pcb fab	EuroCircuits	1	130	130
3" pvc pipe	mcmaster	1	20	20
pipe cap	mcmaster	3	4.27	12.81
pipe threaded cap	mcmaster	2	4.45	8.9
lip seal	mcmaster	4	2.94	11.76
Gear motor	pololu	1	7.99	7.99
Encoder	Amazon	1	9.95	9.95
LiPO	sparkfun	2	12.95	25.9
				0
total				**463.5**

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