STINGER

Fast Acquisition Real-Time Tracking Machine

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1 Executive Summary

In today's society, our lives are very dependent to the technology that we have in hand and use every day. As the technology advances, we come up with new ways to make our lives safer and easier. Robotic systems are one of the very useful technological advancements that have been developed to serve human's needs. One of the applications of these system deals with automatic detection of specific objects of interest. Object detection is mainly used for safety systems and military operations. In this project, our goal is to design an autonomous vehicle that is armed with a high-power laser gun. The robot is designed to detect balloons of specific color and eliminate them using a laser beam. This system is considered a prototype of a larger scale detection system that can be employed in a battle field. The possibility of elimination of human soldiers can save many lives, and it can also improve the performance of military operations in the field.

In the design and implementation of our robotic system, we paid careful attention to three main components that make the robotic system function properly. In the image processing portion of the design, we have implemented a color-based detection algorithm that detects the colors that are very distinct and solid. We made sure that the color object detected is in fact a balloon by performing a validation test based on areas. Using the results of the image processing and the inputs from the distance measuring and obstacle avoidance sensors, the vehicle automatically approaches the target of interest. Our robotic system is very robust to changes in illumination of the environment to some extent, and the control unit of the robot is solely based on software that is interactive with the sensors outside of the robot. The system can be accessed through a Personal Computer using Wi-Fi. Through Wi-Fi, commander can command the robot to attack the balloon of interest.

In this paper, we will be presenting the entire design and implementation of our system. First, we compare different parts and IC chips from multiple manufacturers, and we select the best components based on quality, performance, and price. We then provide a thorough explanation of the basics of image processing, power management, safety measures and communication protocols in the research section. Using the knowledge attained from research we start the implementation of the power supply unit, image processing, and PCB design. In the design and implementation section, we include the implementation of both hardware and software. The design section is consisted of block diagrams, schematics and flowcharts for software based design. We will also be describing the engineering standards and constraints that were effective aspect of our design and implementation procedure. Lastly, we would discuss the administrative duty that provide a summary of project millstones and the estimated cost of the implementation process.

2 Project Description

The Fast Acquisition Real Time Tracking Drone is a proof of concept autonomous robot that is designed to demonstrate a broad range of applications that can be used for Department of Defense, law enforcement, or private/commercial sector. The drone is capable of autonomous detecting and tracking of specified objects contained inside a library. The drone is operated and controlled inside a wireless network range; however, future upgrades may allow the drone unrestricted mobility through GSM (Global System for Mobile Communication) technology. Our team of engineers have designed a low-cost, light weight, completely mobile autonomous drone that is capable of seeking out specified colored objects; once found, the user is given control authority of an onboard high-powered laser that will vaporize the target of interest.

2.1 Function

When the system is turned on it will prompt the user to select the color of interest. After the target is defined in the system, it will first look around to find the target. If the target is detected, it will send a detection success command to the commander who is in charge of the system. It will then approach the target within a specified distance. This system is to continue tracking unless commanded otherwise. Once the vehicle is within a specified distance of the object, a low powered green laser will be activated from the robot to pop a balloon. The vehicle's' battery should be easily replaceable for immediate reuse, when the battery has drained. The batteries should be rechargeable, to alleviate reoccurring expenses for the consumer. The functionality of the system must be independent of the environment in which it is operating to some extent. When we say to some extent, we really mean that the system must be familiar to its surroundings for proper functionality, if it is not familiar to its surroundings, it may malfunction due to confusion. *Figure 1* is a basic illustration design.

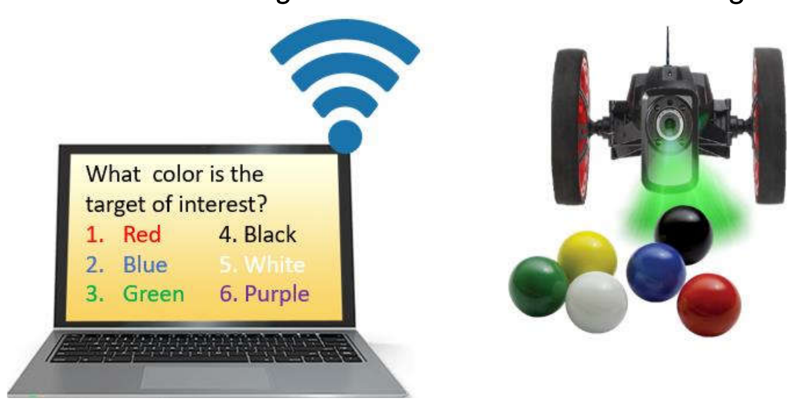

FIGURE 1- BASIC FUNCTION ILLUSTRATION OF STINGER AUTONOMOUS VEHICLE

2.2 Motivation

The world of image processing is both vast and robust. Advancements in this field are steadily rising due to the high demand in both commercial and government industries. Image processing alone does not contain the complexity for many of these company's needs, for this reason, the field of computer vision blurs the line between human biology and robotics. A new generation of intelligent cameras has risen from this field, facilitating high-level analysis of both images and videos, the same way the human brain assigns information to imagery, using both visual and auditory acuity. Our motivation for this project is to take a basic of-the-shelf RC vehicle and completely reconstruct it, equipping it with modern technology such as: autonomous track and detection, mid-range wireless communication and real-time video feedback.

2.3 Goals and Objectives

- The probe vehicle will have the ability to autonomously navigate an environment that is unfamiliar to the operator
- The probe vehicle will be able to autonomously seek out different color balloons with the use of image processing
- Robust to noise and occlusion
- Multi-terrain operability
- The operator will have a ground control station which provides a live feed from the perspective of the probe vehicle
- The operator will have the capability of commandeering control of the probe vehicle at any point in time in order to navigate to and from the site or in case an object of interest is apparent to the operator but not the probe vehicle
- The probe vehicle will communicate with ground control via Wi-Fi (or other RF technology) on a dedicated wireless network

2.4 Prior Art

There are some off-the-market products that closely coincide with many of the features our vehicle has; however, the differences make our product/design both unique and desirable for a variety of customers and applications. Some of the products already out on the market that are similar to ours are Parrot Jump Sumo Drone, the AlphaBot, and some various military/D.O.D drones.

2.4.1 Parrot Jump Sumo Drone

The Parrot Jump Sumo Drone *(Figure 2)* sells for around $50-$80 U.S. dollars from online retailers. The cost is actually quite impressive for the technology. The drone is equipped with an onboard color video camera, Bluetooth receiver, rechargeable Lithium Polymer batteries, LED status lights, and is operated through a smartphone. Some of the key differences in our vehicle that the Parrot Jump Sumo Drone fails to deliver is the ability to add or customize. Our vehicle allows the operator endless flexibility by using a Raspberry Pi development board. Our vehicle boasts longer operational run times with its added battery, it also well exceeds the thirty meter RF range used by the Parrot Jump Sumo Drone by using a WiFi module. The biggest game changer is the ability to track and detect objects autonomously, which makes the Sumo drone inferior.

FIGURE 2-PARROT JUMP SUMO DRONE ©

2.4.2 Alphabot

The Alphabot (*Figure 3)* is a modular robotic vehicle that is equipped with a Raspberry Pi. The price ranges from $50-$150 U.S. dollars. The product has be well developed and fine-tuned, its hard to live up to such a phenomenal product and is really more of something our design aspires to be like. The Alphabot can serve a multitude of functions like our product. Part of the chassis makes up the electrical plug-and-play circuitry which lowers the cost some but also makes the vehicle highly susceptible to damage.

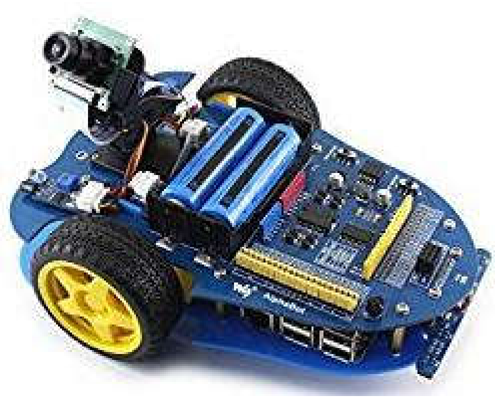

FIGURE 3-ALPHABOT ©

It does however not include the OpenCV image processing track and detection features that our design does. The Alphabot has no enclosure so the electronics are completely exposed to the environment, making it highly susceptible to environmental damage and risk to shock. Our design will be fully enclosed, giving it a little extra protection and ruggedness. The Alphabot will do obstacle avoidance, and follow painted lines using IR tracking; however, those alone leave the product a little juvenile and lackluster.

2.4.3 Military/D.O.D geared drones

Commercial and private industries have really channeled a lot of their efforts into military/defensive use of drones. Many of these vehicles have extremely robust systems onboard and are capable of doing advanced image processing, track and detection operations like our vehicle. Their high dollar value does not allow for large sales; with our vehicle, we hope to provide a reliable and extremely capable vehicle without driving up the cost significantly.

2.5 Specifications

The specifications listed below were primarily determined from the consumer end point needs, and were derived using the house of quality measurement tool. The engineering team has honed in on the specifications of our design listed below.

2.5.1 1GB LPDDR2 SDRAM

The amount of data that will be crunched by the Stinger is fairly large. We will be incorporating real-time image processing and live feedback to a control station. In addition to these tasks, the Stinger will need to handle commands instantaneously and for this reason, it is necessary to have a sizable amount of memory.

2.5.2 1.2 GHz Quad-Core Processor

The Stinger will need to be able to handle a large throughput and react at the blink of an eye. The amount of processing power necessary to perform such a feat cannot be accomplished simply by a microcontroller. We will need to use a microcomputer with an advanced processor to do all the heavy lifting.

2.5.3 Sufficient Internal Memory

The size of the code will be significant because in addition to the standard instructions necessary to give the Stinger life, it will need to be trained. This training information will need to have a sufficient amount of storage to allow the Stinger to maintain an appropriate response time.

2.5.4 RF Connectivity

One of the requirements that we have set forth is that the Stinger must be able to communicate with the operator. It needs to be able to transmit live video as well as receive affirmative commands when ready to fire. This is a potentially hit or miss situation so these commands need to be received and ready for processing as quick as possible.

2.5.5 Camera Interface Capability

The Stinger relies on its ability to see the environment and make snap judgements based on the information that it receives. It will need a camera interface that has a low enough latency that it will not miss a fast moving target, but a high enough resolution that it will be able to distinguish a threat from a bystander.

2.5.6 UART/SPI/I^2C

Because the Stinger already has an immense task list and we need to build this device on a limited budget, we will need to hand off some of the more mundane tasks to a microcontroller. For this to be possible, the microcomputer will need to communicate the necessary information to that microcontroller in the fastest way possible. This exact communication protocol will be investigated in a later chapter.

2.5.7 High Power Laser with Logic Control

As the name implies, the Stinger is a force to be reckoned with. It will sport a powerful 500mW laser that will give it the ability to destroy any positively identified threats. The laser is user commanded and should only be operated by trained individuals who are familiar with laser safety operation and their classes. The laser can annihilate a specified target with a matter of milliseconds, thus should be used with extreme care.

2.6 House of Quality

The house of quality (HOQ) in *Figure 4* is a graphical product development tool/product which helps to aide in an overall quality product. The house of quality consists of an easy to follow matrix, which bridges the engineering design team and consumers' wants and needs. The diagram highlights the product's features, such as, capabilities, aesthetics/appeal, cost, product quality, form factor, durability, etc. Each criterion is rated with level of importance from the engineering standpoint and from the consumer marketing standpoint. Intersecting interests help prioritize the importance of specific functions; which allows the team to tackle specific areas of interest strategically.

Our engineering design team has constructed a HOQ as seen below depicting the marketing requirements set by the consumers versus those from our team. In our design, we are goal-oriented in driving down the overall cost of the vehicle in order to appeal to the market. Increased costs limits the the product's marketability. Our team is striving to eliminate unnecessary latency by optimizing software without taking on highly priced hardware. Also, the battery life is a big hitter in this design project, so our team is focused on power efficiency.

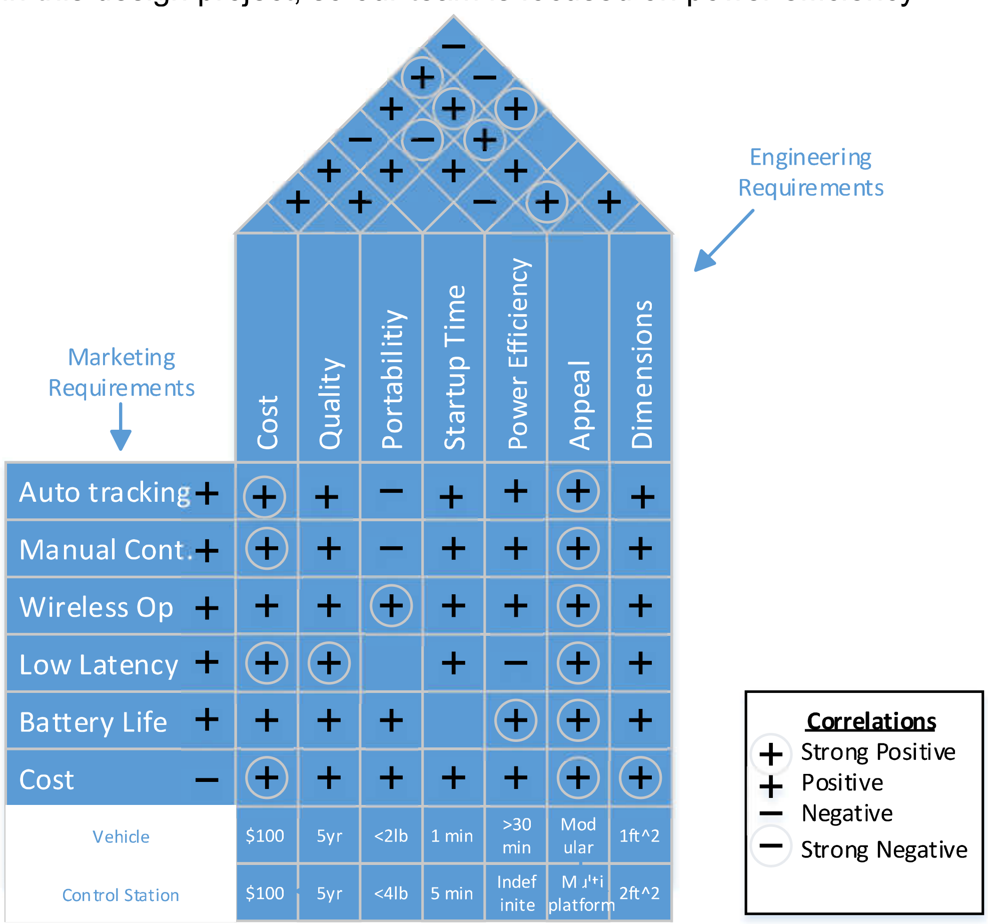

FIGURE 4-HOUSE OF QUALITY

2.7 Hardware Block Diagram

A rough concept design of the planned hardware control for our senior design project is shown in *figure 5*.

- Replaceable battery
- Microcomputer PCB is the master of this design, performs the calculations and provides control signal
- Some of the DATA lines are to provide a way for all the peripherals to relay information to the master.
- Peripherals with same color are to be assembled as one single module
- GREEN: Battery Management System; YELLOW : Micro processing/detection ; BLUE : BMS subcomponents; Grey: Vehicle Platform Purple: Control

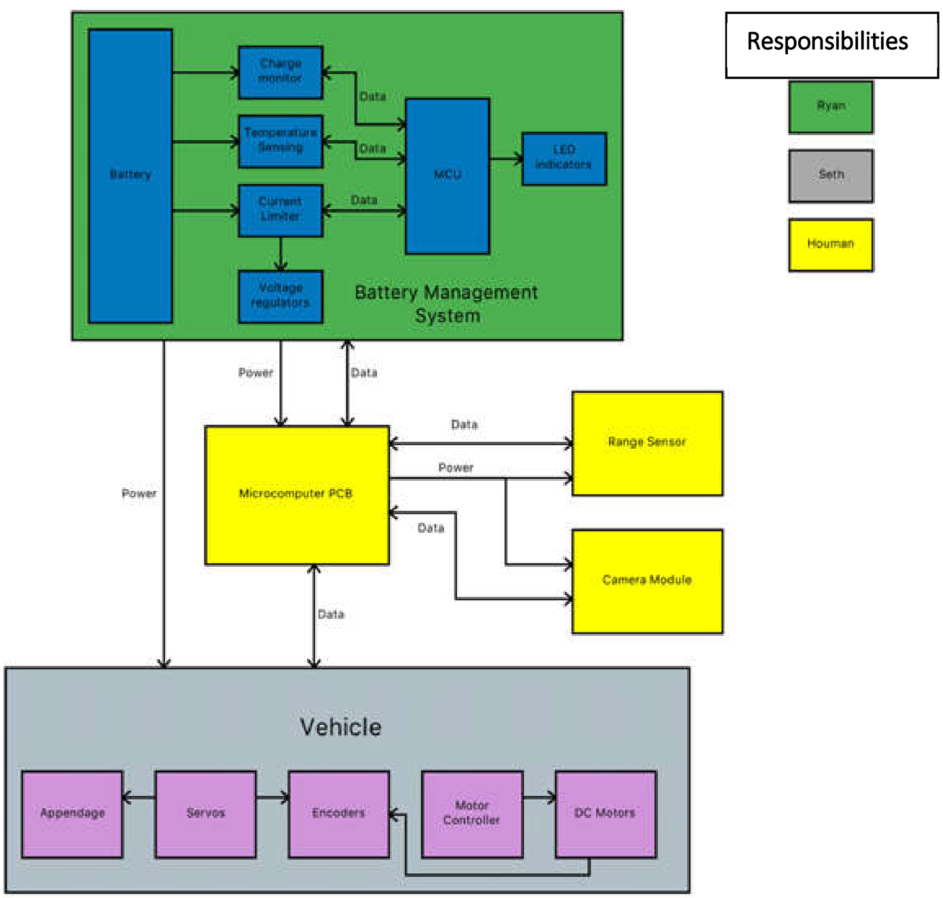

FIGURE 5-STINGER AV BLOCK DIAGRAM

2.8 Stinger Command Flow Chart

A high-level flow diagram (*figure 6)* shows how the robot will operate. The simplistic logic flow allows for low latency and high effieciency.

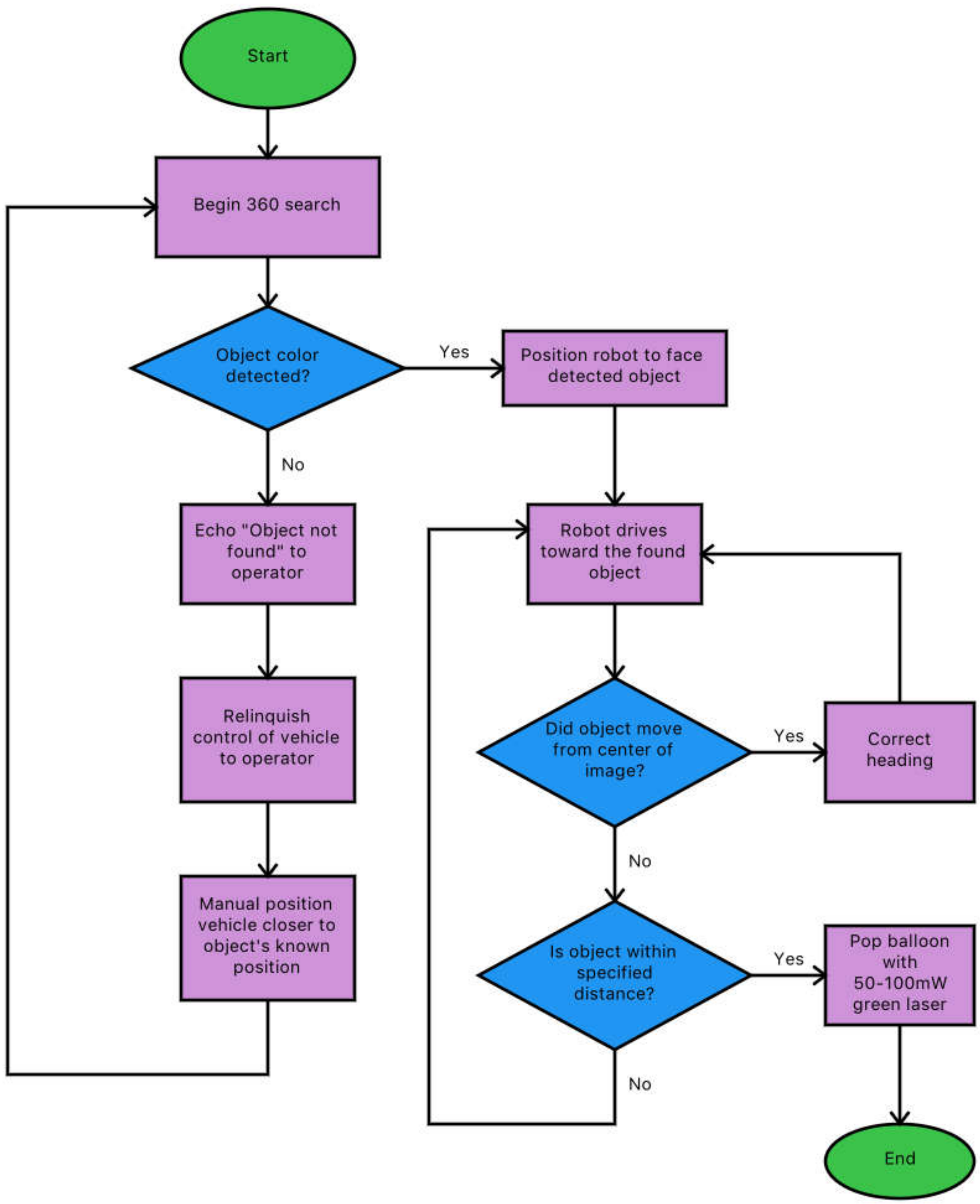

FIGURE 6- STINGER COMMAND FLOW CHART

2.9 Feature selection

Some of the key features worth noting in our design project are listed below. The below features are what our design team considered to be of high importance in which allowed the team to better grasp the high level understanding, concept design, and effort required for our project. These features are what we deem critical in the production of a successful end item product; and is the expected market deliverable.

2.9.1 Battery Supply

Determining the voltage requirement for our project was not an easy decision, since it relied heavily on the approach of our design. We needed to consider how much computing power we actually needed/wanted in order to achieve the video image processing. We also needed to factor in what kind of control system we wanted for the vehicle. Depending on the size of our DC motors would require larger voltage supplies and higher draws of current. The size of the vehicle played a factor, as well as the total run-time of the vehicle off a single, full charge.

Our determining factor for battery source boiled down to the few heavy hitters of power consumption on our vehicle. Those devices were the Raspberry Pi, DC motors, and laser module. The Raspberry Pi requires a 5VDC/2A power source, many of suggested DC motors required roughly 7VDC (Add Amperage) , and the laser module which operates off of 2.6-6VDC/.45 milliamps. A single cell battery would not perform adequately under these load demands, even with a boosted circuit. The decision was made to add another 3.7 volt Lithium Polymer battery. This would give us 7.4VDC nominal without a huge impact on cost or design.

2.9.2 Two Hardware PWM Channels

To drive each of the main motors individually for steering and balance, we need individual control signals that get sent to a motor controller. There are a variety of different types of motor controllers that accept various types of control signals, however PWM is the most common signal type for this application because of its reliability. Using PWM will allow us to control the amount of current through a motor via an H-Bridge motor driver circuit.

2.9.3 Distance sensing

A robot is only as good as its components and features. If the robot doesn't have the ability to detect its distance to nearby objects, it will constantly bump into things and it won't be able to navigate gracefully around obstacles. If the robot detects a point of interest that is occluded, it will need to be able to determine if there are any objects in the way in order to approach that point of interest.

2.9.4 Real-time image processing

The robot needs to be able to see what is in front of it and decipher one object from another. There are a multitude of image processing algorithms available that can do anything from turning an image to grayscale all the way to recognizing key features in an image and sorting them by highest priority. With the added feature of image processing, our robot will be able to detect different colors, shapes and sizes of balloons and make the necessary judgment to pop the correct balloon.

2.9.5 Battery condition monitoring

Rechargeable Lithium Ion or Lithium Phosphor batteries need to be monitored constantly in order to prevent catastrophic failure due to over voltage, over current, under voltage, and over-heating. When a Li-Ion or Li-Po battery is depleted to a zero percent charge, recharging the battery could cause a violent reaction and as such, it is best to have a protection circuit that at a charge level far enough away from zero, automatically severs the connection from the battery to the main circuit. Similar catastrophes occur under the other extreme conditions, so most battery protection circuits take care of all the loose ends in just a single IC package.

2.9.6 High powered laser weapon

Without a task, our robot will just be an unintelligible collection of plastic that follows a target. Many people define success in such a way that it is not mutually exclusive from taking action. We could have chosen to have our robot do a number of things to our target, such as picking up a ball and placing it in a bin or simply pushing a button on said target, but in order to showcase the full extent of our robots image processing capabilities, we settled on utilizing a laser weapon to eliminate a target in a crowd.

2.9.7 Vehicle positional feedback

Our robot needs to be able to precisely control its position. If it is not able to do this, there is a risk on serious injury to the other people in the crowd when the laser fires. Apart from safety, the robot will need to be able to quickly and accurately maneuver around the crowd to seek out and identify its target.

2.9.8 RF Communication

We need a way to manually control the robot either as an override in case of emergencies or just to manually position the robot in a more convenient location to identify the target. RF communication is also needed to transfer information back to the operator. This information could be anything from a live video feed to a permission request for laser weapon deployment.

2.9.9 Low latency motor response

This feature actually ties in with the vehicle positional feedback in a sense that the robot needs to be able to precisely control its position to seek out and destroy a target. If the motors are too slow to respond, the commands for positional correction will be in too much of a lead to the output from the motors. As a result, the robot will miss some commands and will fall behind in performance. With a low-latency motor response, none of this will be an issue because the motors will respond in real-time with the commands sent to them.

2.9.10 Low Power Consumption

Because the Stinger is operating on a battery supply, we would need to ensure that anything in our design consumes as little power as possible. Typical designs for laptops and other mobile devices use switching regulators to assist in fulfilling this requirement. There are a variety of selections of microcontrollers that utilize low power modes of operation and this drastically reduces the amount of power consumed. High efficiency motor control modules can also aid in this matter.

3 Standards and Design Constraints

Standards are ubiquitous among the engineering disciplines. These are what govern the repeatability and quality of processes and products. There are standards that are recognized and utilized nationally, but most big name companies aim to uphold internationally recognized standards. There are a handful of Standards Development organizations that are “not for profit”. They cover a range of fields such as civil engineering (ASTM), medical instruments (AAMI), electrical engineering (IEEE), and building code adherence (UL). Even though some standards developers are not for profit organizations, their standards documentation comes with a hefty price tag. This makes accessing standards a costly venture and is relatively inaccessible to young college students. IEEE, on the other hand, makes their standards free for access 6 months after their initial publication. For this reason, we have chosen to use a very common standard that is employed almost everywhere in any developed country: IEEE 802.11ac-2013.

3.1.1 IEEE 802.11

This standard is colloquially known as WiFi. We needed to be able to initialize a robust line of communication between the Stinger and the operators control station. There were other options available such as Bluetooth, which is also governed by an IEEE standard, but the relatively inexpensive hardware and ubiquity of the WiFi standard was a more enticing option for this application.

3.1.2 JEDTEC Standard for Board Drop Test

This standard applies more in the mechanical domain of this project, but as the Stinger will eventually need to endure harsh terrain, the PCB and its housing will need to be designed such that it can withstand the shock that comes with such a rough environment. This test ensures that the device under test (DUT) can withstand a drop from table height. The JEDTEC Standard 22-B111 is catered towards handheld devices that are typically populated with hundreds of surface mount components. These various packages sizes with differing masses will react in their own way to any amount of sudden shock, so part selection will be guided by the results from these tests.

3.1.3 IPC Standards for PCB Design

A commonly used set of standards in PCB design is the IPC 2220 series. The most general standard among this set is IPC 2221B. This is the Generic Standard on Printed Board Design. It covers topics ranging from simple layout all the way up to complex topics of thermal management and dissipation. The standard covers boards of various complexities including integrated circuitry that uses wire bonding and flip chip. The Stinger will need to have a board design that meets a certain level of professional quality and for this reason, we will need to implement some recommendations from the standard.

3.1.4 ISO 9001 Standards for Quality Management

Many organizations, both large and small can implement ISO 9001 Standards of Quality Management. The exact specifications for the product need to be determined and set by the organization and not by ISO. For this reason, this standard can be applied to many varying fields of product manufacture. The objective of the standard is to ensure that the organization is meeting its customer satisfaction guidelines and producing a quality product. In order to fulfil to requirements on the House of Quality, we will need to use the same structure of ISO 9001.

3.1.5 ISO 1101 Geometric Dimensioning and Tolerancing

Another important ISO standard is ISO 1101. This standard revolves around geometric dimensioning and tolerancing. This is crucial when designing parts that will have a mechanical fit of some form or another. This even includes PCB designs. When designing a PCB, it is usually best practice to design the PCB to fit inside a housing which was designed beforehand. While it is indeed possible to design the housing around the PCB, this adds an unnecessary amount of time to the overall project. This will come into play during our project when we design the enclosure for the Stinger’s electronics. We want the Stinger to have an element of aesthetic appeal that would market itself to the average consumer while also offering the robust operation of a military grade device.

4 Research Findings

Extensive Research went into the engineering and design of our autonomous vehicle. The broad scope of our research covered electrical design, component selection, power supplies, power requirements, implementation, manufacturing, etc.

4.1 Electrical

The electrical portion of this report goes into the finer details of specific components/hardware, their operation, specifications, features, and so on. It covers implementation of laser circuits, BMS, power supply options, PCB design, and microcontrollers.

4.1.1 Battery Management System Overview

The battery management system (BMS) is an integral design when needing to incorporate rechargeable battery sources; which ensures the health, safety, and proper functionality of the hardware and peripherals. The battery management system delivers round-the-clock protection monitoring of the current status/state, data reporting to and from the microcontroller, and ensures safe operating parameters.

Functionality

A battery management system monitors the state and output of the battery, critical outputs (e.g. voltage, current, temperature, etc.) left uncontrolled could cause improper functionality, impromptu and unauthorized resets/shutdowns of the system, permanent damage to hardware or equipment, or worse, injury to personnel/operators.

Voltage

BMS systems manage voltage throughout the system. A BMS system monitors the total voltage of a battery, its individual cells, minimum or maximum cell values, or correct voltage from a voltage regulator. Voltage monitoring is arguably one of the most import features a battery management system monitors, especially when dealing with highly volatile power sources, such as Lithium Polymer batteries. Voltages that exceed the manufacturer’s limit can cause the batteries to overheat to extremely high temperatures. The temperature can get so high, that the batteries may catch fire and release noxious gasses.

Current

The BMS monitors the current output, many electronic devices are sensitive to current, which can cause hardware to malfunction or damage components. BMS systems employ current regulators to allow constant regulated current outputs. If current drives too high or too low, the BMS system is the first responder to allow for a repair, isolation, or restart of the system for safe continued operation.

Temperature

Components such as hardware, motors, or variable loads can put excessive strain on the battery and cause increased temperatures. Temperature can be exacerbated through environmental conditions, climate, altitude, lack of airflow coupled with confinement etc. Excessive heating can cause damage to sensitive nearby components or cause an ignition inside the system. The BMS design safely monitors the system from out of parameter temperatures. In some cases, activating a cooling system or shutting down a portion or the entire system to avoid impending damage. Usually, if a battery is overcharged due to a failure in one of the aforementioned monitoring systems, the batteries can get hot enough to start a fire.

Status of Charge

The state of charge (SOC) can also be monitored to inform the operator of the current state of battery life. The BMS can send signals to non-essential hardware/equipment when the state of charge has dropped below a specified value. This can allow the device to operate at a reduced power setting; thus, optimizing the battery for extended use.

Status of Health

Similar to the SOC, battery management systems are designed to monitor the status of health (SOH) of a battery. Immediately after manufacture of a battery, the status of health is at 100% or in some cases slightly less. The designer may use any of the following to determine the state of health of a battery: internal resistance/impedance/conductance, capacity, voltage, self-discharge, ability to accept charge, or number of charge-discharge cycles. It is up to the designer to assign an arbitrary weight (i.e. value) to the SOH of a battery. The application of the device, in many cases drives what is considered a healthy battery, or when a battery needs to be replace. Over time, the health of the battery depletes as the number of charges and discharges increases. Ambient and internal temperatures can have a detrimental impact on the status of health of the battery. The BMS is responsible for alerting the operator when a battery is no longer sufficient for use and requires replacement or refurbishment.

4.1.2 Battery Management Controllers

The battery management controller IC's are the brains of the battery management system circuit. In this section we researched various battery management controllers offered through different manufacturers. The top three candidates are described in the following sub sections.

Microchip MCP73831/2

The MCP73831/2 devices is a highly advanced linear charge management controllers for use in space-limited, cost-sensitive applications. The MCP73831/2 is available in an 8-Lead, 2 mm x 3 mm DFN package or a 5-Lead, SOT-23 package. Along with their small physical size, the low number of external components required make the MCP73831/2 ideally suited for portable applications. For applications charging from a USB port, the MCP73831/2 adhere to all the specifications governing the USB power bus. [1]

Texas Instruments BQ21040

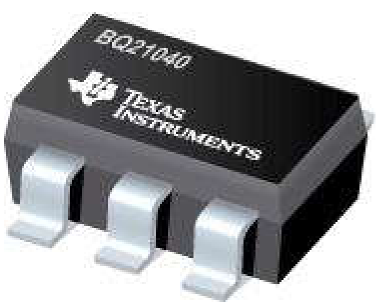

FIGURE 7-BQ21040 BMC

The bq21040 (*Figure 7)* device is a highly integrated Li-Ion and Li-Pol linear battery charger device targeted at space-limited portable applications. The device operates from either a USB port or AC adapter. The high input voltage range with input overvoltage protection supports low-cost unregulated adapters. The bq21040 has a single power output that charges the battery. A system load can be placed in parallel with the battery as long as the average system load does not keep the battery from charging fully during the 10-hour safety timer. The battery is charged in three phases: conditioning, constant current and constant voltage. In all charge phases, an internal control loop monitors the IC junction temperature and reduces the charge current if an internal temperature threshold is exceeded. The charger power stage and charge current sense functions are fully integrated. The charger function has high accuracy current and voltage regulation loops, charge status display, and charge termination. The pre-charge current and termination current threshold are fixed to 20% and 10%, respectively. The fast charge current value is programmable through an external resistor.[2]

[1] Miniature Single-Cell, Li-Polymer Charge Management Controllers (MCP73831/2 Datasheet)
[2] bq21040 0.8-A, Single-Input, Single Cell Li-Ion and Li-Pol Battery Charger Datasheet

NXP MC34673

The MCP73113/4 are highly integrated Li-Ion battery charge management controllers for use in space-limited and cost-sensitive applications. The MCP73113/4 devices provide specific charge algorithms for Li-Ion/Li-Polymer batteries to achieve optimal capacity and safety in the shortest charging time possible. Along with their small physical size, the low number of external components make the MCP73113/4 ideally suitable for portable applications. The absolute maximum voltage, up to 18V, allows the use of MCP73113/4 in harsh environments, such as low cost wall wart or voltage spikes from plug/unplug. The MCP73113/4 devices employ a constant current/constant voltage charge algorithm. The various charging voltage regulations provide design engineers flexibility to use in different applications. The fast charge, constant current value is set with one external resistor from 130 mA to 1100 mA. The MCP73113/4 devices limit the charge current based on die temperature during high power or high ambient conditions. This thermal regulation optimizes the charge cycle time while maintaining device reliability. [3]

Comparison Overview

An overview of component costs is shown below in *Table 1*.

TABLE 1- BATTERY MANAGEMENT COST COMPARISON

Manufacturer	Part Number	# of cells	Cost	Unit
Mirochip	MCP73831/2	Single	$0.59	ea.
Texas Instruments	BQ21040	Single	$0.14	ea.
NXP	MC34673	Single	$0.44	ea.

BMC Final Decision

The teams choice boiled down to the battery management controller integrated circuit made by Microchip and the BMC manufactured by Texas Instruments. Although the Microchip made for and exemplary choice, it was the most costly BMC of the considered the IC's. Therefore, our team has chosen the Texas Instrument BQ21040 integrated circuit due to cost, size, ease of implementation, and minimal additional components and circuit protection features.

[3] Single-Cell Li-Ion/Li-Polymer Battery Charge Management Controller with Input Overvoltage Protection Datasheet

4.1.3 Different Types of Power Supplies

Power supplies range in usage and capability as they do types. There is a broad range of power supplies available on market varying in price, size, rechargeable, non-rechargeable, varying capacity/voltage, weight, shape, so on and so forth. Some various types we are familiar with are Alkaline batteries (AA,AAA,C,D), Nickel-Metal Hydride batteries; which many consumers use to for their rechargeable devices, Lithium Polymer, Lithium Ion, etc. In this section we discuss Alkaline and rechargeable Lithium polymer and Lithium Ion batteries.

Alkaline Batteries

Alkaline batteries possess many advantages in terms of reliability and robustness. These batteries are rated to 1.5 volts and roughly 1.1 volts nominal. They have a low internal resistance so that most of the power is dissipated in the load, instead of the battery. This property is desired so that our remote control vehicle would be able to operate for longer periods of time. It is also versatile and comes in various sizes, such as: AA, AAA, C, and D sized batteries. These batteries are suited for operation in a wide range of temperatures. Leakage current is low in these batteries, so the batteries can be stored for long durations of time. An additional highlight of alkaline batteries is the shear convenience. These batteries can be found at most any local consumer goods store. They are relatively safe, as long as they are properly used and contain a hard metal casing to prevent damage to the battery as seen in *Figure 8.*

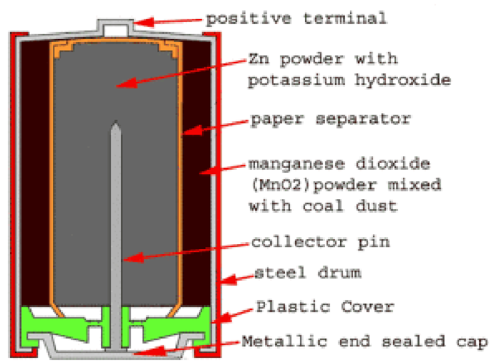

FIGURE 8- ALKALINE BATTERY

All of these batteries provide the same voltage; however, the current varies with the size. AAA batteries are able to produce roughly 1100mAh, while AA batteries can produce almost twice of that. However, the downfall is in the weight and volume. Our vehicle will be loaded down with motors, circuitry, peripherals, and so on. Weight plays a large factor in the performance of the vehicle. The heavy the vehicle, the stronger the driving motors will need to be, which will in-turn demand a higher volume of current, both depleting out power source and requiring even more batteries to satisfy the load. Our vehicles designed to be portable, and for that reason, we have decided to go with a reduced form factor, to be easily carried by hand, stowed, or transported in small packaging.

To analyze this a little further, AA alkaline batteries each supply 1.5V and usually have a capacity up to 2500 mAh. Suppose two cells were connected in series, one would then have a total voltage of 3V, but the capacity would remain the same at 2500 mAh. Most microcontrollers will not operate at anything below 3.3V, so we would need yet another cell in series for a total of 4.5V. If another series set is connected in parallel with the first, the voltage would be the same 4.5V, but the capacity would double to 5000 mAh. This is a total of 6 AA batteries. Typically, one AA battery weighs about 23g. If we have 6 cell--that is almost a whopping one-third of a pound, not to mention the space that those batteries would need to occupy in our design. Unfortunately, these batteries are also non-rechargeable; therefore, the consumer is required to purchase new batteries once they have drained. Depending on the usage, the batteries may only last for a day, the cost of the batteries would soon outweigh the cost of the vehicle, and this is highly undesired. For this reason, the use of AA batteries is out of the question.

Lithium Ion Vs. Lithium Ion Polymer Batteries

There are a number of types of lithium ion batteries, to indude but are not limited to:

- Lithium Ion
- Li-Ion
- LiIon
- LiCo

These batteries can typically be identified by similar shape characteristics which are either rectangular or cylindrical. The casing is robust and made of a strong hard-shelled material for protection against impulsive shock and impact. These types of batteries can typically be founder in larger devices.

Lithium Ion Polymer cells are usually rectangular, and not cylindrical like the aforementioned Lithium Ion batteries. They are typically lined in a metallic colored soft casing. The shell is softer and slightly compressible, which can make it susceptible to damage if not protected. Lithium ion polymer batteries are widely used in small portable devices due to their size, weight, and smaller capacity. These batteries lend themselves for smaller devices like drones, cellular devices, RC vehicles, small robots, MP3 players, etc. These batteries are sometimes called:

- Lithium Ion Polymer
- Li-Poly
- Li-Po

Lithium Ion Polymer Battery (Li-Po): Li-Po batteries as see in *Figure 9* are typically marked with 3.7V or 4.2V. This is because the maximum voltage of the Li-Po cell is 4.2V; however, the “nominal” average voltage is 3.7V. The battery operates at 3.7V for majority of its lifespan. Once the battery drops to 3.4V, the battery is considered “dead” and at 3.0V the battery is disconnected from the load by cutoff circuitry located onboard the battery. Li-Po batteries pack a lot of power into a small area, making their power density high. This also makes them volatile, and so they must be treated with care. Charging of LiPo batteries must be done appropriately. Overcharging a Lithium ion polymer battery can destroy it or cause fire. Li-Po battery charging should be greater than 3.0V, not to exceed 4.2V.

Both Li-ion and Li-Po batteries are suited for our design project. They pack a higher density than rechargeable Nickel-Metal-Hydride (Ni-MH) and Nickel-Cadmium (NiCad) cells and Lead-Acid batteries, while still maintaining the added benefit of being rechargeable and light weight. The ability of lithium ion (Li-Ion) and lithium polymer (Li-Po) cells to charge and discharge more than 1000 times, without a reduction in performance, makes them environmentally friendly as well. Increased mass production of these cells has made this technology more economical. The culmination of these factors is quickly making rechargeable lithium cells the preferred power source for portable electronic devices. [4]

FIGURE 9-TYPICAL LIPO BATTERY

Onboard Protection Circuitry (OPC)

Since lithium ion/polymer batteries are susceptible to permanent damage due to over and undercharging, it is essential for our design to contain protection circuitry that will maximize our batteries lifecycle and reduce safety concerns.

Some manufacturers install onboard protection circuitry directly to the battery. The circuit can typically be found underneath a colored film. If there is no circuitry installed, these are considered raw cells and are not protected. These should be handled with extreme care.

Five important factors to watch for when charging and using batteries:

1) Batteries should not be charged above the maximum safe voltage. This is usually taken care of by the OPC.
2) Batteries should not be discharged below their minimum safe voltage. This is usually taken care of by the OPC.
3) Do not draw more current than the battery can provide. This is usually taken care of by the OPC.
4) Do not charge them with more current than the battery can take. This is usually taken care of by the OPC.

[4] Kovalcik, Michael. Constructing a Lithium-Ion/Polymer Battery with an Imbedded Protection Circuit Module (PCM)

5) Be careful not to charge batteries above or below certain specified temperature range. This is usually between 0-50 degrees Celsius; however, temperatures may vary. This is typically handled by the charger; however, these extreme temperatures usually do not pose an issue in many cases

These factors will be a top priority and concern in the development and design of our project. These aforementioned items will be incorporated into our protection/battery management system design, to avoid any inadvertent damage to the battery, hardware, or user.

Charging Hazards

Due to the volatile nature of Lithium batteries, they must be monitored during charging. A single cell LiPo battery is much more straight forward charging process. A single battery should not be overcharged past its maximum voltage, or exceed the rate of charge of the battery. However, when dealing with two-cells, such as our design, we will require added protection. Since batteries do not charge proportionally in series, they increase the risk of catching fire due to overcharging. A three pole double throw switch will be included into our design, to allow for the batteries to charge in parallel for even charge distribution. The BMS sees the two batteries as if they were one. When charging is complete, the switch can flipped to the discharge position, putting the batteries in series for sufficient power as shown in *Figure 10*.

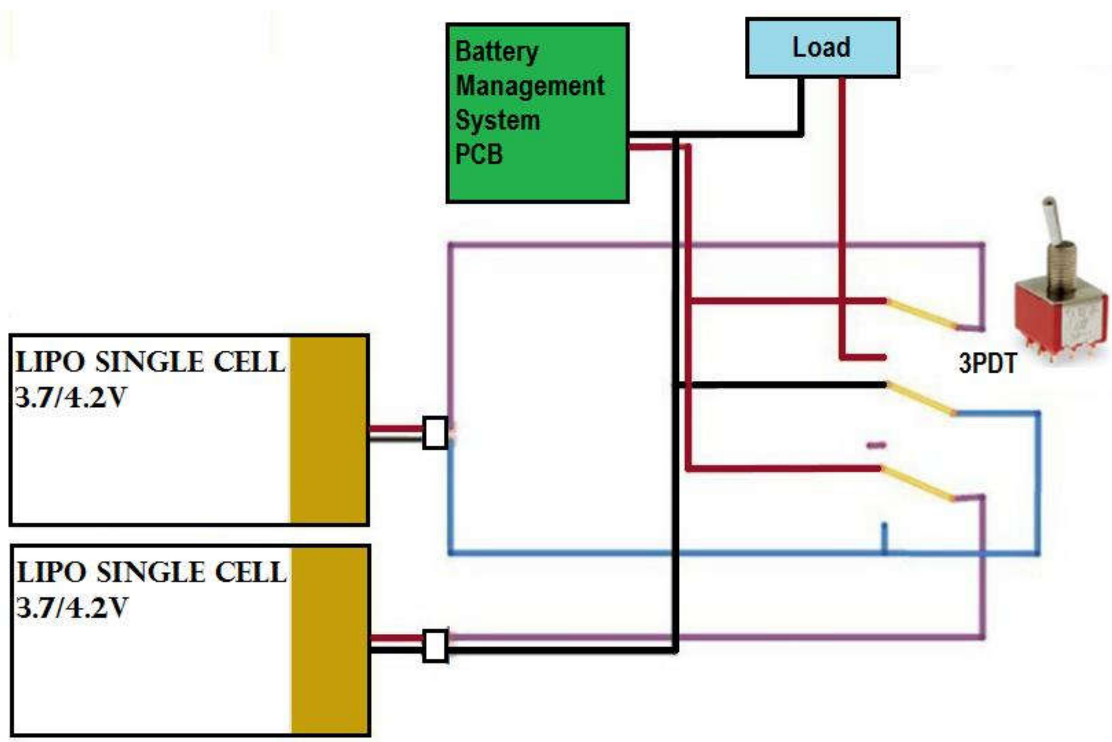

FIGURE 10-MANUAL SWITCHING SYSTEM FOR CHARGE HAZARD MITIGATION

Battery Comparision

Below in *Table 2* is an overview of different types of potential power sources our design team considered, along with some of their specifications.

TABLE 2-BATTERY COMPARISON SUMMARY TABLE

Battery Type	Volume (cubic inches)	Weight (g)	Capacity (mAh)	Voltage (V) Max/ Nominal	Recharge Capable	Number of Cycles	Cost (dollars)
Alkaline (AAA)	0.24	12.00	1150	1.5/1.2	No	One time use	1-4.00 (4pk)
Alkaline (AA)	0.51	24.00	2122	1.5/1.2	No	One time use	1-4.50 (4pk)
NiMH (AA)	0.51	26.00	1000	1.5/1.2	Yes	1000	7-14 (4pk)
Lithium Polymer	0.61	20.00 (Raw)	1000	4.2/3.7	Yes	300-400	5-10 (ea)
Lithium Ion	0.61	22.68	1000	4.2/3.7	Yes	300-400	5-10 (ea)

4.1.4 Final Decision of Battery Supply

We have chosen to use 4.2/3.4 volt lithium polymer batteries for our design project for their cost to energy density ratio. Also, the batteries occupy much less space and are light-weight making them well suited for a portable robot and maintaining adequate battery life.

4.1.5 Light Amplification by Stimulated Emission of Radiation (LASER)

Conventional light sources emit incoherent light; such as the sun or a lightbulb. Incoherent light is typically a manifestation of blackbody radiation; where the heating of an object results in energy that we can see in the form of visible light. However, lasers produce coherent light; which has proven its usefulness and necessity in many of today's electronics. The waves produced from a laser result in a beam of light with in phase-identical wavelengths. This section breaks down why we chose to implement a laser in our design, how they work, and safety considerations.

4.1.5.1 Why we chose to use a laser

Our design concept went through an evolution of ideas in order to find just the right-suited application for our robot. It was not enough to just have a low-cost, autonomous robot that used image processing. The robot needed a purpose. Many of the ideas were juggled back and forth, but many of them were seemingly uninteresting. Ideas of mechanical operations were suggested, such as picking up a target. Other ideas were automated navigation, using re-constructible mazes. Finally, the idea of optics was introduced but it still needed a purpose. Knowing that lasers are another form of energy, we decided to capitalize on it. Eventually, we decided on using the heat produced from a laser when passing through an object.

The use and understanding of optics in technology has grown significantly and quickly since its theoretical foundation in 1917.[5] The applications are nearly endless and have been applied through a wide range of fields. The use of lasers can be seen in medical applications, military weaponry, precision measurement tools, digital imaging, optic communications, barcode scanners, etc. In our project design, the laser will be used to pop a specified target balloon. Although, this may seem to be somewhat of a trivial task; it serves a multitude of practical applications. The concept of our design can be used for riot control, threat tracking, robotic law enforcement dispatch, etc.

4.1.5.2 How Traditional Lasers Work

The underlying principle for laser operation is mostly the same through a wide-range of different types of lasers. Some different types of lasers are: gas, chemical, dye, metal-vapor, solid-state, semiconductor, etc.

In a traditional laser, such as a gas laser; the major components consist of two mirrors attached to the ends of a glass tube filled with gas. One mirror is completely reflective so that it does not allow any light to pass though, the other is intentionally imperfect, so that some photons are passed and others reflected. The laser only needs the addition of a power source to begin the process.

Atoms consist of a nucleus and electrons that orbit around the nucleus. Electrons at rest are at their ground level; however, the electron is capable of moving to higher quantized/discrete energy levels (a.k.a. bands). When an atom absorbs a photon that equal to the difference between two energy levels, the electron becomes excited, and can then occupy the higher energy state. Atoms want to return to their resting state; when an electron relaxes into a lower energy

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[5] Singh, Subhas, Zeng, Haibo, Guo, Chunlei, Cai, Weping. Lasers: Fundamental, Types, and Operations

state, that release of energy emits a photon, this process is called “spontaneous emission”. If the photons are pulsed (a.k.a. optical pumping), the atom is hit with another photon before the electron can return back to its ground state; this releases a photon along with its copy. The copied photon has the same phase and frequency, and propagates in the same direction. The copied photons collide with other atoms whose electron has not returned to its ground state, causing for a photon and its copy to be released. This collision occurs over and over, thus amplifying the reaction. The light that passes through the mirror is called “coherent light” and travels in only one direction; unlike the light emitted from a light bulb which propagates in all directions depicted in *Figure 11*.

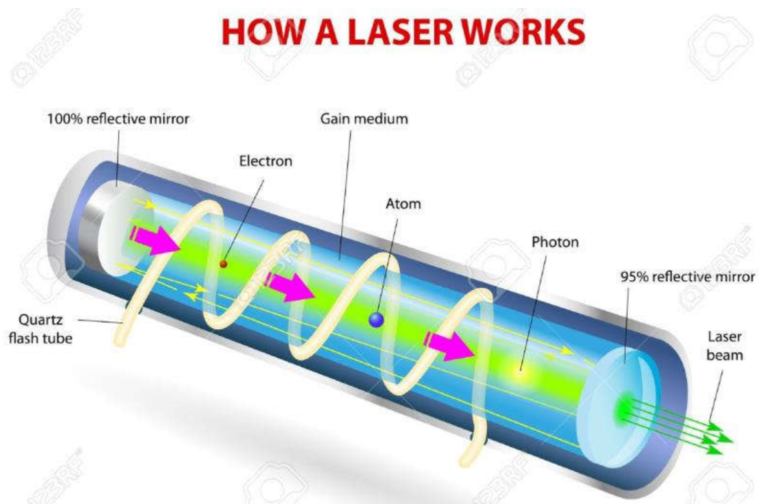

FIGURE 11-GAS LASER

4.1.5.3 Semiconductor Laser

FIGURE 12- TWO CLASS IV SEMICONDUCTOR LASERS

A semiconductor laser as shown in *Figure 12* is a laser that utilizes a semiconductor device in order to produce a beam output. These lasers have many desirable characteristics and properties; which is why they are widely used in many applications. Further detail is discussed next in why we our team of engineers chose to use a semiconductor laser and how it works.

Why we chose it

Semiconductors are extremely successful in today's use. Some of the benefits include extremely low cost fabrication due to the extensive use of semiconductor devices used currently. The medium that the semiconductor uses has enormous gain. Also, unlike the gas laser previously discussed, the semiconductor laser does not require a fragile glass tube that can be easily broken and must be handled with care. The efficiency of many semiconductor diodes is nearly 100% from the output of photons with respect to the injected photons. These lasers occupy very little space, roughly only a few centimeters in length. Lastly, these lasers have low threshold current and consume very little energy. These features make it an ideal choice for our specific design criteria.

How it works

The semiconductor laser converts electrical energy into light. This is made possible by using a semiconductor material. The semiconductors laser requires a semiconductor device. The device is composed of multiple layers seen in *Figure 13*. The materials used in the semiconductor will determine the color of light that is emitted. A P-N junction is created using P-type and N-type semiconductor materials. Some common materials used for semiconductor lasers are:

- GaAsInP produces red light
- GaP produces green light
- GaN produces blue light

A large forward bias allows for the recombination of holes and electrons. When the electrons and holes combine, the electrons must lose some energy, the energy loss produces a photon.

The semiconductor device needs to be fine-tuned in order to direct the photons and to allow for higher refractivity inside the cavity, so that the photon will bounce around and excite the release of even more photons. To achieve this, the walls of the cavity are coated with a highly reflective material on top and bottom. Sometimes a Bragg reflector is used, this allows for optimal refractivity. Bragg reflector can be seen on the bottom side of a compact disc, the refractor is what produces the color spectrum seen on compact discs. The sides are cleaved, most of the light is allowed to exit on one side, producing the laser. The other side may allow for far less photons to escape and uses the information to regulate the voltage to the laser diode.

The light that exits must then be focused, a collimated lens is used for this purpose. A single lens focuses the cone of light exiting the laser diode into a narrower beam that produces a narrower spot over a longer distance.[6]

[6] http://www.madehow.com/Volume-7/Laser-Pointer.html

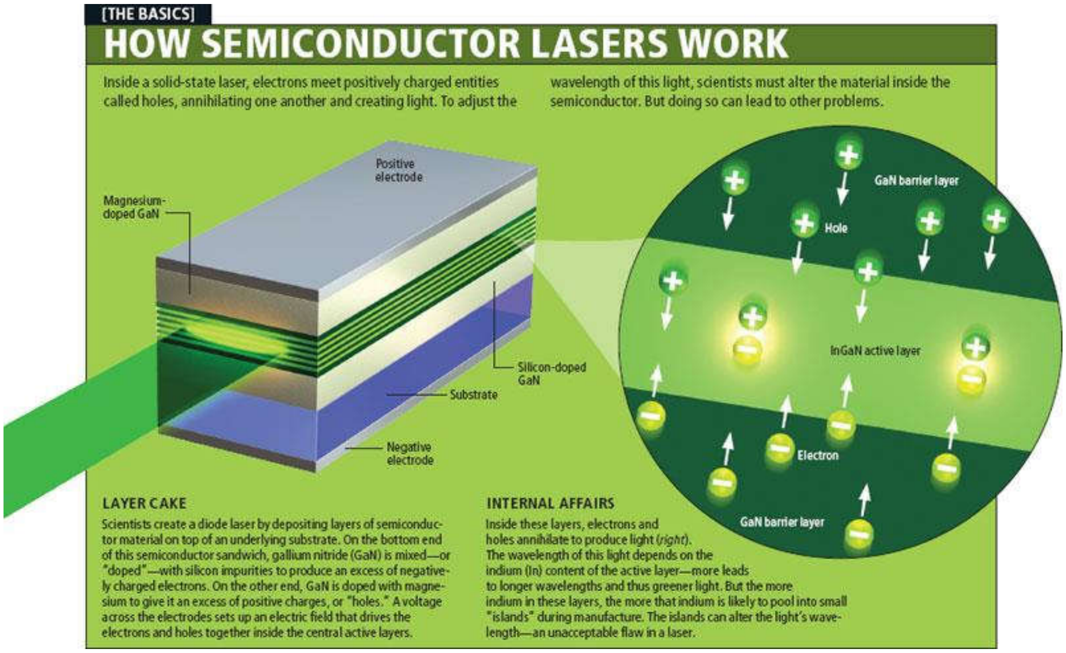

FIGURE 13-HOW SEMICONDUCTOR LASERS WORK

4.1.5.4 Laser Safety

Lasers present serious potential hazards to when not handled properly. That why it is imperative to understand the associated risks, concerns and proper handling of lasers. In this section we dive deeper into the various classes of lasers, their risks, proper protective equipment and mitigation factors. Proper understanding will ensure success in the design and its ability to be used in the market.

Class Identification

Lasers are classified according to their potential to cause damage to an individual's eyesight. In many states, distributors/manufacturers are required by law to indicate the class of a laser in print or label. There is a total of four classes lasers are assigned to. Within each class are sub classes to better specify the terms of use. Each class is denoted either by traditional Arabic numerals or Roman numerals, both are acceptable.

In our project, we will be dealing with lasers that are in the visible range of the electromagnetic spectrum. Lasers that emit a wavelength in between the range of 390 nanometers to about 700 nanometers are considered to be visible light; however, the customer should be aware that some wavelengths may still be very hard to see with the naked eye; thus, the user should take sufficient safety precautions when dealing with these lasers.

Class I/Class 1:

Class I lasers emit a beam of less than 0.39 milliwatts. Lasers that are of Class I do not pose a threat to unaided exposure. This class is safe for long-term intentional viewing. Class I lasers may contain a more hazardous laser embedded in the enclosure of the product; however, according to medical knowledge, the radiation is not harmful enough to escape. No burning of the skin can be caused with class I lasers.

Class II/Class 2:

Class II lasers emit a visible beam of less than 1 milliwatt. At this power, Class II lasers are still very dim and momentary, direct, unaided contact does not pose a considerable hazard. Unintentional exposure of less than 0.25 seconds is still considered to be “safe” by medical knowledge. However, individuals should not intentionally expose themselves to Class II lasers for any extended period of time. The maximum ocular hazard distance of this class (NOHD) is about 23 feet, or about the distance of classroom environment. This class does not pose a skin burn hazard.

Class III/Class 3:

Class III lasers are broken up into two sub classes which are Class IIIR and Class IIIB. Class IIIR emits a visible beam between 1 and 4.99 milliwatts. In this class, the user should exercise caution and avoid direct eye exposure. Unaided-accidental exposure to the eye either directly or reflected light beam is still considered “low” risk; however, the user should avoid direct or reflected exposure to the beam. The NOHD is considered to be about 250 feet, and is not considered a burning hazard.

Class IIIB lasers emit a beam of 5 to 499.9 milliwatts of power. The user should exercise warning when using this class of laser and avoid exposure to the beam. At this power, directed or reflected light poses an imminent hazard to the individuals’ eyesight. The NOHD for this class is 520 feet, which is almost the length of two football fields. This class is considered “generally safe” for diffused reflection exposure (e.g. the light projected off a non-reflective surface such as a wall). Lasers of this class can heat materials such as the skin at close range.

Class IV/Class 4:

This class is the most severe and emits a beam greater than 500 milliwatts. This operator should avoid any direct/reflected eye or skin contact. Lasers of this class will cause immediate eye damage or skin burn. The maximum nominal ocular hazard distance for this class is greater than 733ft at 1 watt of power. Lasers of this class can cause an afterimage effect, where the operator can still seal the dot even after the beam has been extinguished. The greatest care should be used when dealing with lasers of this power. *Note*: The NOHD provided for these lasers was measured using green light. For red light, divide the distance by 5, and for blue, divide by 20.

The Effects of Lasers on the Human Body

Lasers produce an intense, highly directions beam of light. The emitted light is absorbed through other objects and materials, such as a balloon in our project design. When the light or energy is absorbed, the energy is converted into heat; thus, raising the temperature of the object. We capitalize on this energy transfer to pop the balloon in our senior design project; however, the effects of this can cause serious and permanent damage on a human eye. The eye is sensitive to light and absorbs different wavelengths, high powered lasers such as the one in our design can be absorbed into the eye and have damaging effects on the retinal region of the eye. The radiation due to energy absorption can cause thermal effects on the tissue and/or photochemical effects for emitted beams with short wavelengths. Doctors use this process when performing laser eye surgery. The eye is most susceptible to harmful, irreversible damage due to lasers. Operators must also be wary of skin exposure for high output lasers that are Class III and Class IV. For our applications, we have chosen a class IV laser which has an output of roughly 470mW. Our primary goal and objective is to deliver safe and dependable product. During development, we plan on taking all the necessary precautions in order to do so.

Safe Operation and Injury Mitigation

Safety is of utmost importance in our design project for both the designing engineering team, as well as the customer. When dealing with high powered lasers such as Class 3B or Class 4 lasers, proper protection equipment must be used to mitigate injury to personnel. Also, personnel working or operating the equipment should be familiarized with the type of laser on-board, its capabilities, damaging effects, and proper protection equipment. Proper protection equipment can be broken up into two categories: Eye Protection, and Skin Protection.

Eye Protection:

Operators should wear proper eye protection illustrated in *Figure 14* that is suitable for the specific laser being used. The eye protection should filter out the harmful light so that adjustments can be made while operating the laser. Protective eyewear may include full cover/partial cover glasses, goggles, or face shields with filters or reflective coating.

Below we will discuss the suggested/recommended requirements when purchasing proper laser safety glasses. To ensure proper safety during operation of any high-powered laser capable of damaging eyesight, all personnel operating within the hazardous distance should be properly equipped with laser safety glasses, even if not directly handling.

Proper eye protection should:

This list is not all inclusive; however, it is a well-defined guideline

- Provide enough visibility to move about safely.
- Be able to withstand the maximum power of laser radiation likely to be encountered.
- Be able to absorb the specific wavelength of radiation that is being used.
- Be clearly labeled with wavelength they are designed for, the optical density at that wavelength, together with the maximum power rating.
- Be inspected periodically by the laser operator to ensure that pitting, cracking and other damage will not endanger the wearer.[7]

FIGURE 14-GENERIC LASER SAFETY EYE WEAR

Skin Protection:

When dealing with lasers, skin injury can occur through thermal burns from exposure to high powered, highly focused beams and photochemically induced injuries which can occur from chronic exposure to scattered UV radiation.
For adequate protection, protective clothing should be worn. For maximum protection, operators should be fully covered. Injuries that occur from lack of skin protection are typically non-threatening and will heal relatively fast.

Development and Design Precautionary Measures

Our team has put safety considerations at the forefront of this design project; therefore, we have consulted with one another heavily and developed injury mitigation procedures for developmental processes during design and test, as well as mitigation through equipment usage.

Mitigation through Equipment and Testing

In order to mitigate injury or misuse of equipment during project design and development, the team has purchased several lasers with different power outputs. The two lowest output lasers will be used for development. The two low output lasers include a 532 nanometer/50 milliwatt and 532 nanometer/100milliwatt green laser. These lasers are considered Class III, and can cause hazardous effects through direct eye contact; however, it is generally safe through diffused light. Protective eye equipment will be worn at all times of operation of these lasers. The low output lasers do not produce enough heat to burn materials, so no protective equipment is required. The low output lasers will be used to test target acquisition, system integration, and power consumption.

[7] https://ehs.research.uiowa.edu/personal-protective-equipment

The high output 405nm/500mW laser will be used only in the final design and when undergoing testing for operational functionality, heat dissipation, and true power output. All operations will be done within the minimum required time to complete the functional checkout and testing, avoiding any unnecessary, prolonged usage. All proper protection equipment will be worn during time of use, to include both eye protection and skin protection equipment/garments. Only authorized essential personnel shall be permitted during operation of high powered laser testing during development, and design phases.

Mitigation through Design:

In order to maintain a highly-controlled environment, the laser firing circuit will be designed so that it will only receive the required signal voltage through manual input by the operator. The user interface will prompt the operator when the vehicle has located target, is centered upon the target, and is within the specified range. Once all parameters have been satisfied, the terminal screen will ask the permission to activate the laser. The vehicle will remain in position until further direction from the user. The user has positive control over the vehicle at all times.

Once the operator has commanded the vehicle to fire the high output laser, the software will be written so the laser output operates for the minimum required time in order to destroy the balloon target. Our desired goal is to limit the laser to a fraction of a second. Operator should ensure the area is clear behind the target to include any flammable or combustible materials, bystanders, animals, and reflective surfaces. This can be achieved by outputting a picture or video feedback to the operator.

The last design mitigation is placement of the high output laser. The laser shall not be directed or angled upward to which it may come in contact with a bystander(s). The laser will be placed as low as possible and parallel to the ground. The laser will remain fixed and will not be able to adjust its trajectory to prevent stray firing. The vehicle will only be trained to track and detect balloons of a specified color.

Next, we will move on from laser operation and safety and start discussing the teams plans for PCB design. Considering a large portion of our time and the impending success of our product hinges on the successful design and operation of the PCB, we will spend a considerable amount of time discussing the ins and outs of PCB construction, layout, design and purchasing through the assortment of inner continental manufacturers, so that we can produce a high quality product to our customers.

4.1.6 PCB Design

A Printed Circuit Board, or PCB, is a cleaner and more robust alternative to circuit building that uses etched copper traces as a medium of inter-component wiring. When designing Printed Circuit Boards, there are a number of things to look out for. The most obvious thing that one must be mindful of when laying out a PCB is that the traces do not overlap on the same layer. Traces are the wiring interconnect between devices on a PCB.

4.1.6.1 Schematic Design

The first step in creating a really solid product is to design the schematic in such a way that makes it readable and easily understandable by the end user or any technicians who may need to troubleshoot and diagnose an issue. Most if not all PCB design software packages come with a built-in schematic design feature. This feature gives a vast array of parts in a library, allowing the user to find the parts required to build a circuit.

Adding Parts

The Add tool in Eagle will pull up this library and one can choose from any number of manufactures for the component or simply do a search for the part, making sure to specify the correct package. Many parts will share a symbol with other parts, which is why selecting the correct package is so important. Packages can range from tiny form factors like BGA and TSSOP32 to larger, through-hole DIP chips with 40 or more pins.

Grouping of Parts by Function

A good practice when designing a schematic in a software package like Eagle is to strategically place each component in groups by function. For example, if one is laying out a schematic for a Raspberry Pi Compute Module, that person will need to sort all the power and ground connections and keep them separate from data connections like USB and HDMI. Many professionals will keep these categories on separate sheets. If a connection from one category to another is required, for instance power and ground for USB, a reference tag can be placed in both sheets drawing a virtual connection between the two.

Organizational Information and Version Tracking

In order to not lose track of which page belongs to what function, it is also good practice to include some basic information about each category on their respective pages. This information should be organized and positioned on the page so that each and every page has the required information in the same exact location. This makes it easy for the end user to flip through the pages to find exactly what section that they are troubleshooting. Many professionals will include a frame around the schematics on each page. This frame consists of a coordinate reference along the edges that is commonly found on maps. In the bottom, right hand corner of the page, all the identifying information related to that schematic and the project should be included. Important pieces of information to include in this section are as follows:

- Title of the schematic (by function)
- Name of the engineer who drew up the schematic,
- Date the schematic was drawn
- Name of the engineer who double checked the schematic
- Date the schematic was checked
- Name of the engineer who approved the board for order
- Date the board was approved
- Title of the overall project
- Revision letter
- Drawing number
- Any relevant company information or disclaimers

In the top, right hand corner of the page, the revision history should be included. This information describes what changes were made to the design and when they were made. This is important for version tracking in case a particular change did more harm to the design than desired.

4.1.6.2 Component Selection

As stated in the section about schematic design, it is important to select components that have a footprint that will minimize the amount of space required on a PCB but also can handle the amount of current and voltage that the design calls for. Because our design is meant to fit into a small bounce car, space is at a premium. For this reason, we will need to choose the smallest components possible.

Microcontroller and its Power Requirements

The microcontroller that we chose to use in our design comes in a VQFN package, which measures only 4mm x 4mm. QFN stands for Quad Flatpack No Leads. The fact that this package has no leads means that we are able to populate the board with the components packed much closer together. The microcontroller runs off 1.8 V – 5.5 V so we will need to supply it with something in that range. For this reason, we have opted to use a 3.3 V buck converter. The benefit of using a buck converter over just a regular linear voltage regulator is that the switching action allows the unit to operate with a much higher efficiency. In order for the buck converter to work, we needed to also select an inductor and two capacitors. According to the datasheet, the input and output capacitors are both recommended to be 10μF and the inductor should be 4.7μH.

Raspberry Pi and its Power Requirements

The Raspberry Pi requires 5 V and 2 A to operate. For higher CPU and GPU usage, it is recommended to have a supply capable of delivering 2.5 A. For this reason, we opted to use the MIC2177 buck converter. This chip is ideal for battery-powered applications where a high efficiency is necessary. The use of buck converters in our circuit instead of linear voltage regulators means that there will be more components required. The higher density of components yields an even greater challenge when laying out a PCB. While this would normally influence our decision the other way when choosing between a linear regulator and a buck converter, the efficiency is one of those requirements that is imperative to the success of the design. It is good practice to try and minimize the number of components required in any circuit design.

Battery Management IC Package

The battery management system in our project utilizes a BQ21040 charge controller. This IC is packed into a tiny SOT-23 6-pin package which only measures 3mm x 1.75mm. Being that this IC performs the bulk of the functions of the battery management system, including temperature monitoring, it is the ideal choice for component selection based on spatial requirements.

4.1.6.3 Fabrication Facility Selection

There are several different places that one could order a PCB from. Having a board fabricated professionally not only adds to the aesthetic appeal of a design, but also minimizes the risk of having inadvertent shorts in the circuit.

Homemade Option

For the average hobbyist, one method of making boards at home that often yields these poor results is the use of a ferric chloride etching solution. It is possible to transfer a circuit layout pattern to a bare copper clad board using a toner transfer. Toner transfer is the process of transferring a pattern from a sheet of paper that was printed using a laser printer to a copper clad board. The process requires application of heat and pressure. Often people will use cheap store-bought laminator machines to do this. Once the toner has been transferred to the copper, the board is submerged in the ferric chloride acid solution and agitated until the design has been completely etched. The toner will prevent the acid from etching the areas that have been covered. Once the board has been etched, it is removed from the acid and washed in distilled water to remove any remaining acid. The result is a copy of the design in copper. One can then solder the components to this board, but must be very careful to not inadvertently bridge connections. The reason this is such an issue is because homemade boards like this lack what is known as a solder mask. The solder mask is that layer of material that is typically green on many professional boards. The function of the solder mask is to insulate between pads and prevent the solder from bridging between component leads. A pad is an exposed section of copper on a PCB with the sole purpose of maintaining a soldered connection to a pin on a device.

Professional Options

There is a wide selection of fabrication facilities that one can choose from to have a board manufactured professionally. A valuable website to check before ordering any boards is called pcbshopper.com. This website allows one to input several parameters such as board dimensions, copper thickness, whether or not there are gold fingers (e.g. PCIe cards) in the design, and it even allows one to choose from a wide array of colors for the solder mask. Some of the most notable board houses for the hobbyist level are OshPark, Seeed Studio, and EasyEDA.

OshPark:

OshPark is probably one of the most widely known sources for getting PCBs made. This is because of the batch ordering philosophy that they adopted. Typically, board houses will require that one fills out an entire panel with the PCB designs. This is good when trying to minimize the amount of wasted material, but it is not so great for the average consumer who can’t afford to pay for an entire panel. PCB panels are very large and can vary in size. One example of a PCB panel size is 24” x 18”. The maximum usable area of this panel size for a double layered board design is 23” x 17”. One of the biggest challenges people face when panelizing their board designs is nesting the shapes of the boards to the best efficiency possible. This is where OshPark and the other listed board houses come into play. For these services, they take several orders per day and use optimized scripts to panelize the boards to the maximum efficiency and only charge the board designer for the space that their board happened to take up on the panel. OshPark was one of the very first to use this ideology effectively and the added marketing tactic of using a proprietary shade of purple for the solder mask helped them rocket to the top of the charts of popular board houses for the average hobbyist. When comparing the quality of the boards that are made by OshPark to those of a standard board house, it is about the same. There are some limitations to what OshPark can do, such as the inability to process blind and buried vias, but for the boards that one might see on a day to day basis, this isn’t an issue. A via is a continuation junction of a trace from one layer of a PCB to another layer of the same PCB. The pricing from OshPark is affordable for small boards as they only charge $5 per square inch.

Seeed Studio:

For larger boards, a better choice for board fabrication is the use of Seeed Studio. They have the same batch ordering ideology as OshPark, but they operate in China, so as a result, the boards are less expensive. Compared to the quality of the boards from OshPark, Seeed Studio has many similarities. One of the most common issues that crops up on boards ordered from cheap board houses is that the drill holes are not always lined up perfectly or centered on the pads and vias. One wouldn't think much of this except that the minimum radius for the annular ring of one of these elements is a very strictly enforced specification on many hardware design guides. Many SoC and ASIC manufacturers will publish this guide in order to inform the design engineer of the different requirements when laying out the traces and also selecting crucial parts for the operation of said SoC or ASIC. Many hardware design guides will suggest a range of values for passive components like resistors, capacitors, and inductors. Seeed Studio doesn't usually have issues with misaligned drill holes, but one quirk that seems to upset some of their customers is that they silkscreen an order number on the board. Many people show their artistic expression when designing their PCBs and this is often done on the silkscreen layers. When a board house just randomly places these silkscreened numbers on the boards, it can sometimes interfere with the designs aesthetic appeal. For boards that are just going to end up in an enclosure of some sort, this is seldom an issue.

Lead Times (OshPark VS. Seeed Studios)

The lead time for boards that are ordered from OshPark vary from one to two weeks. They offer a service called Super Swift Service that charges the same cost of the board (so twice the cost in the end), and this guarantees that the board design will be panelized and sent to the fabrication facility on the same day. As said earlier, this is wonderful for really small board designs, but for the larger designs, this can quickly get very expensive. Seeed Studio doesn't fall to short of the same lead times that OshPark offers, but instead of a separate service billed on the order, one simply pays for DHL express shipping which is around $15. All in all, the combined lower cost of the boards themselves plus the express shipping, Seeed Studios comes out to be cheaper still than OshPark for larger board designs.

A requirement that many companies have is that their boards are ordered from board houses that are located in the United States. China has a reputation for copying designs and repackaging them in a cheaper way to resell them. This is really bad for companies who seek to profit from their designs and so ordering from a company like OshPark would be in their best interest for prototypes. After the prototyping stage, the best thing for them is to panelize the boards themselves and just order the whole panel from the board house.

Easy EDA:

EasyEDA has an online PCB design tool that allows people to piece together their ideas for a board while they are on the go. One of the drawbacks to this, however, is that this design suite does not include some of the most important features that are found in more popular and professional packages like Eagle and Altium. One of the features that EasyEDA lacks are the standalone capabilities of a PC-based software package. To use it, a web browser and an internet connection are needed. Another key thing that gets overlooked often is the security of the designs. When one does a board design locally on a package such as Eagle, one doesn't have to worry as much about designs and intellectual property getting stolen, but when a design is saved in the cloud as it is with EasyEDA, there is always a risk that the account could be hacked into and the design stolen. The nice thing about EasyEDA, however, is that one is able to order boards directly and immediately after the design is complete as the web-based tool is integrated into their board ordering system.

4.1.6.4 PCB Layout

PCB design software packages include a whole suite of useful tools to get started on designing a full-fledged printed circuit. The first step in designing the board is to complete the schematic design and most PCB design packages allow one to do that and then generate a baseline collection of part footprints to position strategically in the board outline.

Autorouter:

For simple circuits like a blinking LED 555 timer circuit, this layout is simple and can be accomplished using the Autorouter feature included in Eagle. The autorouter is a tool that is commonly included in many PCB design software packages. The function of the tool is to "guess-and-check" several different variations of trace routes and it will try to optimize the PCB layout according to the design rules that were previously set. This feature saves the design engineer a lot of time in the designing process and can get them straight to the fabrication step. However, for more complex board designs that require either a more tightly packed layout or one that simply has many more connections, the Autorouter tool should be avoided. It runs iteratively to check a wide range of possible connections, but it lacks the ability to reason through placing the traces in a way that allows making all the required connections in a cramped area.

Autorouting is a nice feature and can save time; however, autorouting traces can cause an unsightly design and make the PCB much more confusing for someone who is trying to read the schematic/layout. That is why we will talk about manual placement in the next section.

Manual Placement Strategy:

A way to make manually routing traces a much less arduous task is to first position the components with the highest pin density and then surround it with the passive components that share a direct connection to that part. Many parts will have a connection to ground, so in the end, this will make placement much easier. The ground connection should be one of the last connections to be made. As the components are placed, they should be positioned somewhat concentric with the aforementioned high-density part. When placing the components, it is really important to be mindful of the spacing between each component. One needs to ensure that one will be able to pass the required traces between those components, but not too far apart so as to save space. This will make the board cheaper to manufacture in the end.

Vias:

One tactic that is commonly employed by design engineers is to utilize vias to pass a trace to a point that would be inaccessible if limited to a single layer on the board. Too many vias can be a bad thing. In a good design, one should minimize the number of vias in the board. The reason for this is because vias are inherently higher impedance components than regular traces. For a regular circuit that doesn't involve high frequencies, the only drawback to having a high via count is that the vias generate more heat when used in a single trace rather than to connect two pours on different layers. A pour is a planar section of copper on a PCB layer that occupies the spaces that aren't already occupied by traces, vias, and pads. When used in a high frequency circuit, the vias will behave similar to tiny antennas and this can cause destructive interference on EMI sensitive components like gyroscopes. Therefore, PCB layout is a time consuming and challenging endeavor.

Net Classes:

In order to alleviate some of the time required in layout, many PCB design packages employ identifiers called Net Classes. Net classes are descriptors for the different types of traces that one would expect to have on a board and whose function is to modify the trace width depending on the particular application. These are classifications that can be given to certain connections in a schematic that govern the maximum current that is capable of flowing through any particular type of trace. With this feature, one can separate the power traces from the signal traces and even separate the signals traces on a finer level to those that are differential pairs.

Differential Pairs:

In PCB design, there are often multiple traces running in pairs. These pairs belong to a single signal but are split into positive and negative sides. An example of a connection that will be used in this project that can take advantage of differential signals is the USB connection. When routing differential signals, one of the most important requirements usually listed in the hardware design guide is the required trace width and distance between the two traces of the differential pair. This requirement is known as impedance matching and is important to pay attention to when routing a board so as to minimize signal attenuation in the traces. Much like any other physical object, signals take time to move from one end of a trace to the other end. When a longer trace is used, it will inevitably take longer for that signal to reach its destination. This metric of time taken to transfer a signal is known as the propagation delay. The hardware design guides will usually tell the design engineer if it is important for the passive components to maintain a close proximity to the SoC or ASIC. Also, when working with differential pairs, it is extremely important that the signals on the two traces that make up the pair both leave their source and arrive at their destination within a small enough window of time so as not to attenuate the data being transferred. An important design consideration for differential pairs is that one must take into account the naming convention for the nets in the schematic. In Eagle, they make this easy. For the design software to differentiate between the standard traces and the differential pair signals, one must name the two nets of a pair the same exact thing, with the exception that one should append "_P" and "_N" at the end of the net names. This will tell the software to grab both traces at the same time when routing a pair. This allows the designer to ensure that the two traces maintain the same spacing and, for the most part, length from the starting point to the termination point. When it is impossible to maintain the same trace length in a point to point connection, the designer must utilize a feature called Meander. The Meander tool allows the user to create a diverging path on the shorter of the two traces in a differential pair. The software will automatically calculate the difference between the two trace lengths and if the difference is small enough to satisfy the design requirements for signal propagation delay, the design engineer can then terminate the ends of the trace. Often times, divergent paths on a differential pair will resemble a squiggle with 45 degree corners.

Design Rules:

The types of traces listed will have different properties and as such will need to be routed according to the design rules listed in the hardware design guide as they pertain to the trace width and trace isolation. Design rules are a set of constraints that ensure the design of the PCB does not violate any spatial restrictions for both the components on the board as well as the traces, pads, and vias. These are usually limited by the capabilities of whatever PCB fabrication facility one chooses to use. After these conditions are set in the Net Classes manager, the software will automatically inform of any violations to these rules when manually routing the traces. For nets that require higher currents, the trace will need to be wider. The Net Classes manager will automatically set the trace width of the nets in the schematic, so when routing a trace, the software will set the width.

Trace Angles:

It is often said that 90 degree corners are bad for board design and many reasons have been given. These include increased EMI and so-called "acid traps" where acid will build up during the etching process and cause the design to lose too much material. The fact is that none of these claims are true. For years, board designers have been utilizing whatever routing conventions that seemed to fit best for their design and it was never limited to 45 degree traces, as was exemplified by an old frequency filter built by HP in the 1970's. Back then, boards were made by hand and not with the assistance of computer drafting software. Traces could be routed with any angle and the advent of 45 degree traces didn't come about until CAD software was used for design. This software had a limitation of eight different types of traces that one could implement in a design, so layout was no longer as flexible.

Ground Pour:

The final step in routing a PCB is making all the necessary connections for ground. This can be accomplished in small and sparsely populated circuits simply by drawing a trace from point to point, but when the component count begins to grow, it will be next to impossible to make all the connections without having a large number of vias. To circumvent this problem, it is best to create a pour. The pour is a solid polygon that covers the entirety of the board design and maintains evacuated regions where traces have already been routed. Pours can be renamed in the software to match the net name for the ground connection. This is usually just named "GND". Once the pour has been renamed, the software will automatically recognize the connections from the ground pads on the components to the adjacent portions of the ground pour and will create a connection accordingly.

4.1.6.4.1 Thermal Relief Pads

In Eagle, these connections to the ground pour are a different variation than the rest of the traces on the board. They form what is known as Thermal Relief Pads. A Thermal Relief Pad, sometimes known simply as a thermal, is a pad that shares a direct and somewhat discontinuous connection to the pour surrounding it and facilitates the ability to apply solder to that area without the connecting plane dissipating too much heat. The thermal relief is provided by four discontinuities in the connection and it resembles the spokes of a wheel. The reason for this added feature is to ensure that during soldering, the ground pour doesn't sap too much heat away from the soldering iron. This will ensure that it doesn't cause a cold solder joint.

4.1.6.5 Board Assembly Methods

Once the boards have been fully designed and received back from the fabrication facility was used, the next step in the process is to assemble the boards for testing. For through-hole components this is straightforward. Surface mount components require a bit more attention and are not as easy to desolder for rework. To give a little more insight on the upcoming topics, *Figure 15* illustrates the two techniques/methods.

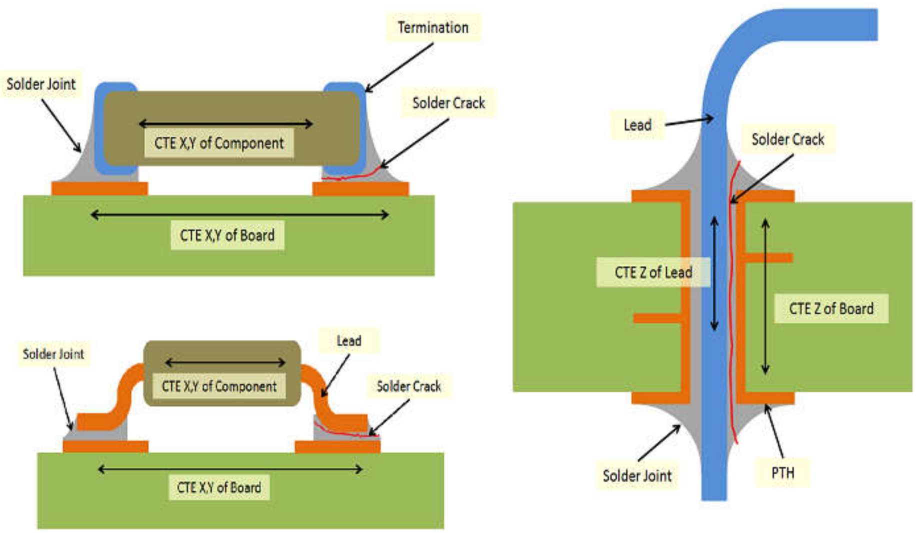

FIGURE 15- THROUGH-HOLE VS. SURFACE MOUNT

Through-hole Assembly:

To assemble a through-hole board, one just inserts the components and solders them in by hand using a soldering iron. Even though this process is simple, it is best practice to assemble one block of the design at a time. This will allow for testing along the way and will reduce the amount of time spend on troubleshooting a bad board design or component. Usually the first section to be assembled is the power supply section. It may even be beneficial to include test points or headers in the design so that an oscilloscope or multimeter will be given easy access to measure the voltage on fine-pitch pins. To facilitate the ability to measure current on the board, often designers will incorporate a zero ohm resistor in the design. This resistor can be removed to open the circuit for testing.

Although through hole is easily done with the use of a solder iron and a little bit of time, it has its share of drawbacks, and so for a clean and efficient application we move to surface mounted devices.

Surface Mount Assembly:

When dealing with smaller surface mount components, it is still possible to hand solder them, but only down to a certain package size and style. For instance, passive components with a 2512 package will be very easy to hand solder just like their through-hole counterparts, but when the component size starts to approach 0604 package sizes, it becomes exceedingly difficult to hand solder if one doesn't have very steady hands and a microscope or some other visual magnifying device. There are techniques for hand soldering very fine pitch ICs, including drag soldering with a chisel tip or point to point soldering with a very fine point pencil tip, but these take an immense amount of time and concentration. Certain IC packages with a thermal mass on the underside may not even allow for hand soldering unless one gets extra creative with the design of the board. One possible way to do this is to incorporate an exposed section of copper on the opposite side of the board and connect that area to the thermal mass with a field of vias. This will allow solder to be melted on one side of the board while the soldering iron is being held on the other side.

Solder Reflow Technique:

By far the easiest way to solder surface mount components, small and large, is by the use of a reflow oven. Reflow is the process in which solder paste, a mixture of microscopic solder balls and liquid flux, undergoes a controlled change in temperature to a point where the solder balls melt and form a solid bond between the component and the pad. The flux in this mixture allows the solder to freely bond to the component and pad by removing any existing oxidation and ensuring that no more oxidation forms on the surface of the metal when heat is applied. The presence of any oxidation will inhibit successful soldering. To achieve the best possible solder joint when reflowing, it is best to follow the recommended reflow profile commonly provided in the datasheet for the component. Sometimes the datasheet will simply say to follow the profile of the solder paste that is used, but if that isn't the case, more than likely it is because the component that is being reflowed is sensitive to high temperatures and cannot be exposed to those temperatures for too long.

4.1.7 Microcontrollers

Every day we use electronic gadgets that simplify our lives. Most, if not all of these objects contain a device that manages and computes all of the mathematical data required to perform complex operations. This device is known as a microcontroller, or MCU for short. The use of microcontrollers varies drastically from one device to another and this variation is made possible by the onboard programmable flash memory. Users can develop their own code that tells the microcontroller what to do with the incoming data and how to manipulate, distribute, and store that information. As time goes on, the capabilities of modern day microcontroller's increase in accordance with Moore's

Law, which states that with each passing year, the number of transistors on a chip will double compared to the previous year. As a matter of simplification, microcontrollers can be seen as tiny shipping warehouses whose foreman delegates tasks to different areas of the shop such as internal records, distribution, receiving, and processing. That foreman is the control unit of the central processing unit. The internal records area of that warehouse is synonymous with the flash memory of the microcontroller. The distribution and receiving areas of the warehouse are the general purpose inputs and outputs common to most microcontrollers. Lastly, the processing area of the warehouse shares the same core operation of the microcontroller. It takes the incoming shipments (data) and sorts parcels to many different orders that have been placed by customers. The distribution area will send off the new packages to the end users. All of this work is closely monitored and recorded by the internal records area so as to not make any mistakes in distribution.

4.1.7.1 Allocation

For the purposes of this project we will need to use at least one microcontroller to handle information processing for any attached hardware devices. The range of possible uses for a microcontroller is vast and as such, we will need to carefully assess the project and determine what functions and processes can be handled by the microprocessor and what needs to be handled by the microcontroller. The tasks that will need to be handled by the microprocessor are those that are heavily computational and that handle a large amount of information from the camera. In order to avoid unnecessarily bogging down the microprocessor with excess tasks, we will inevitably need to delegate some of those tasks to a microcontroller.

MCU Battery Management System Interfacing:

The robot will have certain features that require the computational power of a microcontroller. One such feature is the battery management system (BMS). For this feature to be effective, the microcontroller will need to be able to receive crucial data from the BMS regarding the present charge in the battery and the temperature of the battery. The microcontroller will also need to be able to interpret this data and make an informed decision on what to do in that particular circumstance. Once a decision has been made, the microcontroller will need to send a command to the BMS to take action by either limiting the current draw from the battery or shutting the system down entirely. Because even the BMS is controlled by a microcontroller, it goes without saying that the microcontrollers will need to be as energy efficient as possible. This can be accomplished by sourcing only microcontrollers that are powered by anything less than or equal to 3.3V. It is also necessary that the microcontroller be able to enter a low-power state when it is not actively performing any operations.

MCU Motor Drive System Interfacing:

Another feature that will need to utilize a microcontroller is the robots drive system. Because microcontrollers have direct access to the bits that get read in and sent out, it is one of the best choices for controlling signals to the motor drivers. Due to the fact that the motor drivers interpret a PWM signal as a speed and direction, the microcontroller will need to be able to generate a PWM signal for each motor driver IC. This is fairly common among the many microcontrollers on the market, so sourcing a part for this particular process should not be an issue. Since we will need to have accurate vehicle positional feedback, the microcontroller will need to be able to read and interpret data from some type of encoder as well as a gyroscope and accelerometer. For this reason, the microcontroller will need to have a fast ADC clock speed with enough bits to support the incoming data.

MCU Laser Diode Firing Control

The laser diode used on the Stinger draws enough current that it can no longer be connected directly to an I/O pin. For this reason, we would need to switch the signal to the Laser by using a MOSFET. The control for this switching command can be delegated to the microcontroller as the Stinger will need to accept a confirmation signal from the operator anyway. This adds a level of safety to the project and will ensure that nobody loses an eye due to inadvertent firing of the laser.

4.1.7.1 Types of Microcontrollers

Below the team has gone over multiple MCU's to find out which suits the needs of the design the best in function and cost, as well as offer room for expandability for later revisions of the design. At the end of this section, a table overview of the researched components is given, as well as the teams' final part decision.

ATMEGA8-16AU:

The ATMEGA8 is not the most power efficient microcontroller available, but with 23 I/O, it has similar capabilities to the Arduino Uno. This MCU features a total of eight ADCs, each at ten bits. Out of the handful of MCUs immediately available to our group, this has the most ADCs. If our requirements for analog sensors exceeds our current specifications, this may be a good selection. In addition, because this MCU has a CPU speed of 16 MIPS, it is also not the fastest MCU and therefore does not have a good reason to be more power hungry. Given that the battery that we will be implementing on this project is a 3.7V LiPo type battery, the operating voltage requirements do not fit nicely into the range that the battery can handle. This MCU does not stand up to the other possible solutions.

ATMEGA168-20PU:

The ATMEGA168 family of microcontrollers is a contender in the realm of low-power computing. This MCU boasts 23 programmable I/O, six separate PWM channels, and six 10-bit ADCs. All of these capabilities come at a low cost of only 250µA/MHz at an operating voltage of 1.8V in its active mode. Even with such a low power consumption, the ATMEGA168 still clocks in at 20 MIPS. The obvious downfall, however, is the mere size of the chip. This MCU is a 28-pin DIP package which would take up a significant portion of the PCB. It does come in smaller TQFP/QFN packages but the DIP package is what we have readily available for testing.

ATMEGA328P-PU:

FIGURE 16-ATMEGA328P-PU

This is the microcontroller that the Arduino Uno utilizes. It has all the same specifications as the ATMEGA168, but as this one uses only 200µA/MHz at an operating voltage of 1.8V in its active mode, it is a more energy efficient choice for this project. As with most of the AVR microcontrollers, the ATMEGA328P utilizes single clock cycle instructions. It is also field programmable using an ISP (In-Circuit Serial Programmer). One crucial feature that needs to be mentioned is SPI communication. In order to send and receive data to and from the Raspberry Pi, we need to have some form of communication. The ATMEGA328P has I²C, SPI, and UART/USART. Out of these three types of communication, SPI is the fastest and easiest to connect. This is convenient because the ISP mentioned earlier uses a 6-pin header to program the chip. Those 6 pins are power, ground, MOSI (Master Out Slave In), MISO (Master In Slave Out), SCLK (SPI Clock), and Reset. The ISP that will be used to program our microcontrollers is the AVRISP MKII from ATMEL. Not only is the ATMEGA328P packed with capability at a fraction of the cost, the surface mount package as seen in *Figure 16*.

ATTINY85-20PU:

This microcontroller features two PWM channels which could be useful for driving two motors. It also features a 10-bit ADC which could be used to convert analog signals from our various sensors to digital data that the microcontroller can interpret. According to the datasheet, this particular microcontroller features either four single-ended channels or two differential channel pair channels. A really cool feature of the 10-bit ADC is that it is capable of temperature measurement, which could prove useful for the BMS. One feature that has been seen in several end user products is the capability of in-system programming. On this microcontroller, this is accomplished using a three wire SPI connection. This could be important later on in the project if we make any programming mistakes, as we wouldn't have to remove the chip from the system to reprogram it. The operating voltage range for this microcontroller is anywhere from 2.7 V to 5.5 V. The ATTINY 85V-10PU has a wider operating range at 1.8 V to 5.5 V but also has a slower internal clock speed of 10MHz. If we plan on using this microcontroller in the BMS, we will most likely benefit from using a wider operating voltage range. The ATTINY85-20PU has six programmable GPIO. Finally, one of the most important features of this microcontroller is the low power operation modes. In active mode, the microcontroller consumes only 0.54 mW at a clock speed of 1 MHz. In power-down mode, the microcontroller consumes only 0.18 μW.

ATTINY13A-10PU:

The final option among the AVR microcontrollers available to us is the ATTINY13A. Just like its cousin, the ATTINY85, this microcontroller comes in a very small eight pin DIP package. Its operating voltage range is from 1.8V – 5.5V. The ultra-low power consumption under power-down mode in the ATTINY13A draws only 9nA at 1.8V. Under this condition, the only thing still running are the external interrupts. It takes a minimum of eight clock cycles to begin execution of an instruction if the microcontroller is in power-down mode. Four of these clock cycles are for waking the CPU and the rest are due to the CPUs response time to the interrupt. This microcontroller shines above the other AVR MCUs when it comes to low-power consumption and small form factor, but it lacks the I/O count of the larger AVR chips.

PIC16F688:

The PIC microcontrollers in this selection all have a much slower CPU speed than their AVR counterparts. Programming these MCUs also differs from the AVR MCUs in that it uses a different wiring scheme. For the PIC MCUs, the data in and data out both share a single line. Although the datasheet claims that it has a wide operating range at 2.0V – 5.5V, it is still narrower than the AVR MCUs listed previously. With the baseline voltage at 2.0V, it may not be a good choice to implement in a battery powered circuit that will more than likely fall to that voltage or possibly lower. Another thing to mention is that this MCU doesn't have any dedicated PWM channels. It is probably still possible to generate PWM signals in software, but they won't rely on their own oscillators, which makes it less reliable. A redeeming quality of this MCU is the ultra-low-power operation. In its active mode, at a frequency of 1MHz and an operating voltage of 2.0V, the MCU only consumes 55μA. In the power-down mode, with the oscillators all turned off and the MCU still operating at 2.0V, the MCU only draws 50nA, placing it in a category of one of the lowest power MCUs available.

PIC16F636:

The PIC16F636 is similar to the PIC16F688, but it lacks any ADC channels. This is its biggest detriment. Without any internal ADCs, we would be required to use an external ADC for all of the sensors necessary to the project. The only redeeming quality for this MCU is the fact that in its lowest power state, i.e. when everything is turned off except for external interrupts, it only draws 1nA. This is a decent figure, but a microcontroller is not of much use if it can't accomplish the tasks necessary for the project without the aid of external hardware.

PIC12F683:

The PIC12F683, when compared to the PIC16F688 has the same power consumption, but also has fewer I/O and half the number of ADC channels. It does, however, have a dedicated PWM channel. This doesn't really do much for our project as we would need at least two separate PWM channels to really make use of a stable motor control algorithm.

MSP430FG4618:

FIGURE 17-MSP430 MCU ON DEVELOPMENT BOARD

The MSP430FG4618 (*Figure 17)* is the same microcontroller that is used in the Embedded Systems classes at UCF. This MCU made it onto the list because of our familiarity with the microcontroller and how to program it. Texas Instruments advertises this MCU as an Ultra-Low-Power Microcontroller. While it is a robust chip and has plenty of documentation on its use, it does not perform as well as the AVR MCUs listed earlier. The redeeming quality for this MCU is that it has a whopping 80 programmable I/O. The operating voltage for the MSP430FG4618 is between 1.8V – 3.6V, which is perfect for the battery that we will be using. During its active mode, at a frequency of 1MHz and 2.2V, the MCU draws 400µA. In the power-down mode, the MCU draws 0.22µA. Unfortunately, none of the MSP430 MCUs listed here contain any dedicated PWM channels, but as stated earlier, PWM output can be accomplished via software.

Texas Instruments makes a wide variety of microcontroller units for their customers to meet the extreme range of demands and capabilities. Next we will move on to another model of the MSP430 family

MSP430G2553:

The MSP430G2553 is the same microcontroller that comes with the TI Launchpad. The whole development board only costs $10 compared to the one used in the Embedded Systems classes which costs $117. This is surprising as the CPU on the MSP430G2553 is faster than the CPU on the MSP430FG4618. It clocks in at 16 MIPS, twice as fast as the other MCU. The cost was most likely driven by the number of I/O because the MSP430G2553 only has 16 programmable I/O and eight 10-bit ADC channels.

MSP430G2452:

The MSP430G2452 is the second microcontroller that comes with the TI Launchpad. It has all the same specifications with the exception that it utilizes slightly less power in active mode.

4.1.7.2 MCU Comparison Overview

TABLE 3- MICROCONTROLLER SPECIFICATION OVERVIEW

MCU	Operating Voltages	# of PWM Channels	ADC	# of I/O	Power Consumption – Active	Power Consumption – Power-down Mode	CPU Speed
ATMEGA8-16AU	2.7V - 5.5V	3	8@10-bit	23	**1MHz, 3V, 25°C** 900μA	**3V, 25°C** 0.5μA	16 MIPS
ATMEGA168-20PU	1.8V – 5.5V	6	6@10-bit	23	**1MHz, 1.8V, 25°C** 250μA	**1.8V, 25°C** 0.1μA	20 MIPS
ATMEGA328P-PU	1.8V – 5.5V	6	6@10-bit	23	**1MHz, 1.8V, 25°C** 200μA	**1.8V, 25°C** 0.1μA	20 MIPS
ATTINY85-20PU	2.7V – 5.5V	2	4@10-bit	6	**1MHz, 2.7V, 25°C** 450μA	**2.7V, 25°C** 0.15μA	20 MIPS
ATTINY85V-10PU	1.8V – 5.5V	2	4@10-bit	6	**1MHz, 1.8V, 25°C** 300μA	**1.8V, 25°C** 0.1μA	10 MIPS
ATTINY13A-10PU	1.8V – 5.5V	2	4@10-bit	6	**1MHz, 1.8V, 25°C** 190μA	**1.8V, 25°C** 9nA	10 MIPS
PIC16F688	2.0V – 5.5V	0	8@10-bit	12	**1MHz, 2.0V, 25°C** 55μA	**2.0V, 25°C** 50nA	5 MIPS
PIC16F636	2.0V – 5.5V	0	0	12	**1MHz, 2.0V, 25°C** 100μA	**2.0V, 25°C** 1nA	5 MIPS
PIC12F683	2.0V – 5.5V	1	4@10-bit	6	**1MHz, 2.0V, 25°C** 55μA	**2.0V, 25°C** 50nA	5 MIPS
MSP430FG4618	1.8V – 3.6V	0	12@12-bit	80	**1MHz, 2.2V, 25°C** 400μA	**2.2V, 25°C** 0.22μA	8 MIPS
MSP430G2553	1.8V – 3.6V	0	8@10-bit	16	**1MHz, 2.2V, 25°C** 230μA	**2.2V, 25°C** 0.1μA	16MIPS
MSP430G2452	1.8V – 3.6V	0	8@10-bit	16	**1MHz, 2.2V, 25°C** 220μA	**2.2V, 25°C** 0.1μA	16 MIPS

4.1.7.3 MCU Final Decision

For the purposes of this project, it is best that we use the ATMEGA328P because of its high I/O count, PWM channels, ADC channels, and low-power operation. It is available in PDIP packages which makes it great for breadboarding and developing our code. Once we get our code sorted out, we can order it in a much smaller VQFN package which makes it much more ideal for embedding into smaller projects.

4.1.8 Communication Protocols

We will need to be able to set up and maintain a communication port between the microprocessor and the microcontroller. This data line will transfer commands generated by the microprocessor in response to the image processing results. These commands will be primarily for control of the laser, but there will be room for control of the motors and other devices in later revisions. There are a handful of options to choose from regarding which communication protocol to use, but the limiting factor is the capability of the microprocessor and the microcontroller. It just so happens that both the Raspberry Pi and the ATMEGA328P both support I²C, UART, and SPI.

4.1.8.1 I²C Communication

I²C communication is one of the less cluttered configurations for communication. This only uses two wires to communicate not including power and ground. This protocol uses a half-duplex configuration meaning that it can only communicate in one direction at a time.

SDA:

The first wire is the data line known colloquially as SDA. Through this line, the master device sends a query to all of the devices on the data bus in order to establish communication with just one slave device. It does this by first sending the most significant bit of an address to the bus and continues to append more digits with each query until only a single device responds. At that point, the master knows the specific address for that device and commits it to memory. This process of elimination is known as bit-banging.

SCK:

The second wire in this communication protocol is the clock line, known simply as SCK. This line is self-explanatory in that it provides a clocking signal for the operation of the devices. Only at each clock pulse will the master and slave devices send and receive queries. This keeps everything flowing smoothly just as traffic lights would in a busy city.

4.1.8.2 UART Communication

UART serial communication is also a simple form of communication in that it only uses two wires, but this protocol is not governed by a clock signal and can only communication with a single device. The two lines for UART are transmit and receive, known as TX and RX respectively. An important fact about UART is that when connecting the devices, one must connect the TX of one device to the RX of the secondary device and vice versa.

4.1.8.3 SPI Communication

Similar to I²C, SPI can communicate between several devices and uses a bussed architecture. SPI uses four basic lines for communication. These lines are MOSI, MISO, and CS, and CLK. SPI uses a full-duplex configuration, which means that the master can communicate at the same time as the slaves.

MOSI/MISO:

MOSI (Master Out Slave In), is similar to the TX and RX lines in UART communication but has an easier naming convention to remember. Master Out indicates that the line leaves the master device and Slave In indicates that it enters the slave device. As long as one understands which devices on the bus are slaves and which device is the master, this is a breeze to connect. MISO (Master In Slave Out), just like MOSI, has an easy naming convention and makes connecting the devices on the bus easy.

CS:

The CS line is the chip selector. This is also sometimes called SS for slave selector. This line performs the function previously mentioned in the I²C section of initiating communication with a specific device on the line through bit-banging.

CLK:

The clock line for SPI performs the same function as the clock signal of any other communication protocol in that it keeps all data traffic organized and flowing smoothly.

4.1.8.4 Final Decision for Communication Protocol

The team has decided to use SPI communication as our means of communicating between the Raspberry Pi development kit and our custom designed PCB. SPI allows for the fastest mode of data transfer as well as ease of installation.

4.2 Control System

The control unit of any robotic system determines the complexity of that system. In our project, we would like to avoid feedback controllers because they require measuring sensors that would increase the complexity of our robot. Therefore, we will be using a three-wheel vehicle that will not require balancing. By doing that we are only responsible to generate instructions for the robot to execute using some simple signals generated by the Raspberry Pi. The control unit must be able to work in collaboration with the image processing unit and other sensors' inputs. In order to simplify our project and reduce the cost, we are using the same module (Raspberry Pi) to control the vehicle. In this section, we describe some basic theories in mathematics that will be used to control the DC motors of the robot, and then, we will cover the ways we can interface raspberry pi with heavy inductive loads.

4.2.1 Pulse Width Modulation (PWM)

The RC vehicle is a Three-Wheel system that is controlled by 2 DC motors. We will be using Raspberry Pi to control the movement of the vehicle. Raspberry Pi is capable of generating PWMs using GPIOs. Pulses are great signal for controlling the speed of these motors because they can control the amount of current running into these DC motors. When designing the PWM for this project, we must familiarize ourselves with a few concepts that can affect the behavior of a DC motor and Raspberry Pi.

4.2.1.1 Duty Cycle

First concept is known as the duty cycle of a pulse. The Duty Cycle of a pulse is the ratio of time that a pulse is HIGH over one period/cycle. It is defined as $D = T_{HIGH}/T$. the Duty Cycle is proportional to the DC value of a Pulse signal. If a Pulse is Defined as $P_t = A$ for $-T/2>t>T/2$.

4.2.1.2 Fourier Analysis

We can use Fourier analysis to find the DC value of such signal. By doing so, we find out that the DC/Average value of the signal is equal to the Duty Cycle times the amplitude (A). Hence, we can control the amount of power being supplied to the DC motor by modulating the width of the pulse signal.

4.2.2 DC Motors

Raspberry Pi 3 is capable of generating PWM in a very efficient way, but the problem with raspberry pi is the fact that it is not powerful enough to drive the DC motor. These DC motors usually draw around 600 mA of current from the power source. As we know, if we try to draw that much current from this small module, we will end up burning the device. There are many different motor drivers available in the market that can be used as an interface between a computing module like Raspberry Pi and a heavy load like a DC motor.

4.2.2.1 DC Motor Driver

We will be using a motor driver design by Texas Instrument known as L293D. This Driver is a quadruple high-current, half H-Bridge driver. These devices are designed to provide current to a large array of inductive loads. The benefit of L293D is the fact that all the inputs to the chip has TTL compatibility and also it supports up to 7V of input voltage. L293D is equipped with internal high speed output clamp diodes to suppress the spikes of the inductive loads when the voltage polarity is switched. When operating this driver, we must make sure that we use proper heat sinks so that the device does not exceed it operating temperature.

4.2.3 Control Unit Considerations

There are many other factors that are important when considering control unit of the robot. When designing control units, we must consider the states of the system that needs to be controlled using these controllers. The controller that we are building for this project is a software-based control system that has three states of interest. These states must be controlled during the operation of the system. As we know, in order to control a state, that particular state must be controllable. And since we are using a software-based control unit, that particular state must also be observable. This implies that we need to implement a few sensors to observe the states that are need to manipulate the behavior of the system. The three states that are interesting for this project are:

1) Distance from the target of interest
2) Location of the target of interest
3) Obstacles in front of the robot

4.2.3.1 Target Distance

Distance measurement is one of the most important measurements for this project that must be carefully implemented. Measuring the distance of a target can be done using an ultrasonic sensor. Ultrasonic sensors send a sound wave to the target of interest and measure the change in time for the wave that is reflected from the object. Using the time difference, we will then measure the distance to the target. We will need to make sure that the ultrasonic sensor is fully aligned with the center pixel of the camera module because if it is not aligned it will measure the distance of a clutter with respect to the robot. We will be using an ultrasonic module developed by Sunfounder Corporation as seen in *Figure 18*. This module has 5V input Vcc which is compatible with the Raspberry Pi module.

FIGURE 18-SUNDFOUNDER © ULTRASONIC SENSOR

The sensor is a very simple module that has two pins that determine the functionality of sensor. We will trigger the module by setting the Trigger pin to high, by doing that, we would allow the device to send a pulse of ultrasonic wave. After that we wait until the Echo pin receives a non-zero signal. A non-zero echo signal indicates a reflection. The distance sensitivity is an important factor in our design because it gives the robot sufficient time to escape the obstacle in front of it. If the target is too far away, and we shoot the laser, we will not be able to pop the balloon, or it may simply take too long for the laser to pop the balloon. Using the time difference, we will calculate the distance between the object and the robot. The following equation is used to calculate the distance:

EQUATION 1-DISTANCE EQUATION

$$\text{Distance} = \text{Time Difference} * \text{Velocity of Sound}$$

Where the Velocity of Sound in Free air is 340 meters per second. The accuracy of the calculation is dependent on the time difference that is obtained from RPi's time module.

4.2.3.2 Target Location

This robot will be operating under constant linear and angular velocity. The computer vision algorithm is responsible for detecting the center of the balloon and send three different signals to the motor driver. The first two signals are the turning signal. If the center of the object is to the right of the center pixel (which is 255), the algorithm must send two signals to the two pins that are responsible for the driver's motor pins. The two signals must indicate that the wheel on the right side turn clockwise and the wheel on the left side of the vehicle must turn counterclockwise. If the object is to the left of the center pixel, the opposite of the action should happen. If the center of the object is on the center pixel, signal must be sent to the Motor Driver to drive both DC motors by the same speed.

4.2.3.3 Obstacle Avoidance

Another major issue that we may encounter when testing the robot is the fact that it might run into an obstacle. In order to avoid this issue, we must be able to detect the object of interest and avoid any obstacle that is placed in front of the robot. We may achieve this task by placing an obstacle avoidance sensor that uses infrared reflection principle to detect obstacles. These sensors send pulses of infrared light continuously and measure the reflection of the light. The idea is that if there is an object in front of the robot, most of the infrared light will be reflected to the sensor; therefore, by using an infrared sensor, we can detect the reflections of infrared light off of the obstacle in front of the robot.

Types of Obstacle Avoidance Technology

There are many different obstacle avoidance modules in the market, but we decided to choose the one developed by Sunfounder Corporation. This kit consists of an infrared-receiver, an infrared-transmitter and a potentiometer. The potentiometer is used to change the distance sensitivity of the module. The distance sensitivity is an important factor in our design because it gives the robot sufficient time to escape the obstacle in front of it. If the target is too far away, and we shoot the laser, we will not be able to pop the balloon, or it may simply take too long for the laser to pop the balloon.

Infrared Technology:

In this project, we make use of infrared technology to detect objects that are considered obstacles as seen in *Figure 19*. Therefore, it is important to understand the functionality of this technology. Infrared sensors and devices are used in many different applications. They are used to take satellite imagery, detect black bodies (radiant body) and even cold body. Our project deals with cold or hot body detection which means that an infrared source must be supplied in order to have an accurate detection of objects. There are three main regions in the electromagnetic spectrum that are used for different applications.

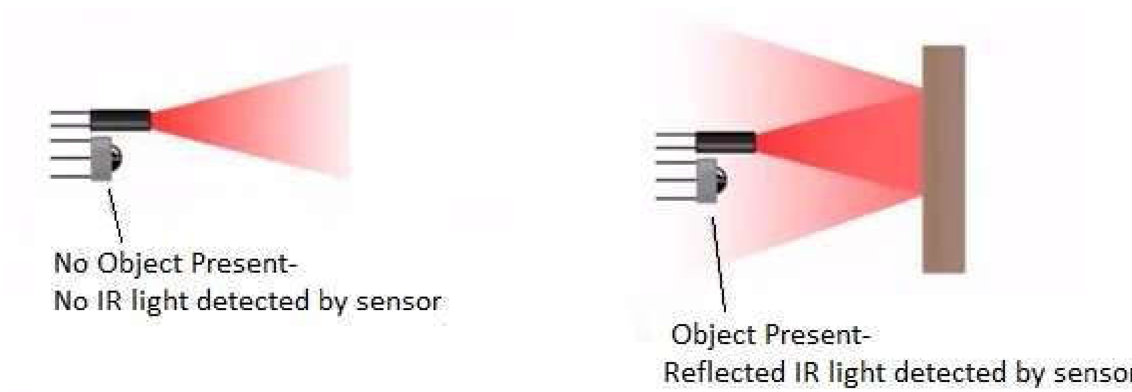

FIGURE 19-OBJECT DETECTION USING IR SENSORS

The first one is called Near Infrared Region (NIR). The wavelength in the NIR region ranges from 700 nm to 1400 nm. It is mainly used for Infrared Sensing and fiber optics communication applications. The second region of Infrared Technology is known as Mid Infrared Region (MIR). The wavelength in MIR ranges from 1400 nm to 3000 nm in the electromagnetic spectrum. MIR region is mainly used to detect high levels of heat. This is really useful for search and rescue missions in areas like jungles or mountains in which humans use fire to stay warm. MIR sensors are used to make automatic fire detection algorithms. Lastly, the third region of Infrared technology is known as Far Infrared Region (FIR). The wavelength in FIR ranges from 3000 nm to 1 mm. FIR is used to perform Thermal imagery. Thermal imagery has many applications in missile technology for detecting and tracking blackbodies of interest. We will be using the NIR type for detecting objects in the front of our robot. The basic operation of NIR sensor relies on two main components that are coupled together. These two components are known as Transmitter and Receiver. The Transmitter is simply an Infrared LED that emits lights in the NIR region. The receiver on the other hand is a sensor that measures the amount of reflection of the light from the object. If the reflection is strong enough, it will generate a signal that indicated an object was detected.

Ultrasonic Technology:

Ultrasonic technology is based on sound waves that are produced at the frequencies that are higher that what we as humans can hear. There are two main applications of Ultrasonic technology that is used frequently in the today's scientific community. The first one is known as ultrasonic imaging that is used to detect imperfections in manufacturing, to accelerate production of chemical based substances, and etc. the second application of ultrasonic technology is for ultrasonic range meter sensors. Interestingly, the idea of ultrasonic technology for range measurement purposes came from animals such as bats. The Ultrasonic technology is mainly used for underwater mission in which the diver needs to have an accurate measurement of distance from himself to the bottom of the ocean. This non-contact based system is now popular in robot systems for designing the control units of such systems.

4.3 Software

Software is the core of any robotic system that needs to be designed in a systematic way so that the robot can run effectively and efficiently. There are many different programming languages that are compatible with raspberry pi module. For the purpose of comparison, we have selected 2 main programming languages that are mostly used for robotic applications. The two programming languages are python and C. both languages are great choices for programming RPi. In this section, we would examine both programming languages and select the one that best suits the application and the constraints of the project. After the programming language of choice is selected, we would go through the development and the structure of the code. In choosing the language of choice we must consider three factors that are essential to both the development phase and the deployment phase. These three main factors are the structure of the program, resources available for the program, and the speed of the program.

4.3.1 C language Vs. Python

C programming language is a procedural programming language that is used in many different applications ranging from writing operating systems to writing image processing algorithms. C programming language is one of the lowest level programming languages that are available for use for free. One of the best advantages of C programming language is the fact that it can be compiled to assembly language efficiently and run faster than any other general purpose programming language. The speed and performance of this programming language has made it ideal for Embedded system implementations.

C-language comes with a diverse set of libraries that are available for free to public. Python on the other hand is known as a high-level programming language. Python is a interpreted language that is very sensitive to indentation. Python is capable of perform the tasks done in C in a fewer lines of code. The language is written is such way that it enables the programmer to write codes that are very readable by humans. Unlike C, Python performs automatic memory management. This feature is very ideal for our projects since we would not need to allocate memory for image manipulation. In other words, memory allocation is done automatically by python interpreter. Python is also an open source programming language with many different libraries available for free to the public.

Both Python and C are great languages for this project, but python has a few advantages that stand out when compared to C. first advantage of Python is the fact that it has a very simple structure that makes it easy to debug. For example, when there is a bug in a C-code, it is very difficult to narrow down the problem if we do not have a very good interface/development environment. Python would inform us what has gone wrong when a code does not run. This capability of python makes it an ideal selection for computational algorithms that involve imagery data. Second advantage of python for this project is the fact that it comes with many different libraries specifically designed for images and arrays. These libraries are used extensively by many different people and a lot of documentations and support is available for developing new ideas from these libraries.

The libraries that we are going to be using for image manipulation and processing are OpenCV, Numpy, Scipy, and MatPlot. The accessibility to resources is the main advantage of python over C. One must say that there is also a pitfall to using python for processing images. The disadvantage that python has when compared to C is the fact that it is not as fast as C programming language when performing image processing tasks. This problem can be tolerated as long as the algorithm is not too computational because we need the program to run in real time and any sort of lagging in the performance would cause the robot to malfunction.

4.3.1.1 Final Decision of Coding Platform

For this project, we will be using Python programming language because of its simplicity and availability of support. Writing computer vision algorithms can be very complex and requires a lot of array manipulation. Python has a library dedicated to array processing which makes it ideal for fast algorithm development. As of now Python is our programming language of choice, but if we ran into performance problems when testing our algorithms, we will have to translate the code to a faster programming language like C. Python is very close to human communication; hence, we can more easily develop and debug our code in python.

4.3.2 High Level Description of Algorithm

When developing complex algorithms that involve many different computations, it is reasonable to break down the algorithm into partitions that can communicate with each other. For this project, we have broken down the entire code into three main entities that are decoupled from each other but provide input into one another. The performance of each compartment is a crucial aspect of the design that must be considered carefully. We must make sure that the number of computations performed by Raspberry Pi module is at its minimum. Hence, if we can avoid certain computations in expense of tolerable accuracy, we must avoid it. Before we describe the nature of the three components of the algorithm, we must pay close attention to the preprocessing tasks that must be performed before these algorithms can be applied.

As we know, an image taken from a low-quality camera contains some noise that is problematic for most of OpenCV functions. Noise is defined as a high frequency component that is randomly added to an image. In order to get a better understanding of noise reduction in image processing, we must consider an important transformation developed by a well-known mathematician named Jean-Baptiste Joseph Fourier known as Fourier Transform. Fourier transformation of an image describes the frequency contents of an image. Images are considered to be two-dimensional signals that are discretized in pixel level. When we take the Fourier Transform of a noise free signal, we expect to get a set of complex/imaginary numbers that have the same size as the original image. In this frequency domain image, the location of each pixel corresponds to a specific frequency value. When the image is noise free, the frequency domain image mainly contains a really high value at the zero frequency and as it moves away from the DC value, the Fourier intensity fades away.

Conversely, when an image is noisy, the Fourier spectrum shows high intensity frequency components. In order to get rid of these noises, we either have to have a statistical model that defines the noise behavior or we need to estimate the noise by some method. For our project, we will be using a low pass Gaussian filter of size 15x15 to blur the imagery. Blurring the images seems to be an unreasonable task that destroys the signal content, but in reality, blurring does not affect the behavior of Computer Vision Algorithms. The second preprocessing task that must be done is known as resolution reduction. High resolution cameras produce imagery that are very costly when used for vision based detection. Hence, we must make sure that we will not be using an image that is 1280x1280. Our goal is to reduce the image size and resolution by the same factor so that we do not lose any signal contents. Therefore, we will reduce both the size and the resolution of the imagery taken from the camera to

512x512. This will provide us with more room to play with when implementing the vision-based detection.

The first component of our algorithm is known as color based detection. We will be using HSV domain Thresholding to filter out colors as explained before. The color-based detection component provides a blob that has the possibility to be a balloon. This blob is dilated using morphology and the results is fed into the second compartment of the algorithm known as interest point detection and matching. The interest point detection is based on the Scale Invariant Feature Transform develop by David Lowe at the university of British Colombia. SIFT will look at the input image at difference scales and selects the points that seem unique in the image. usually these points are the corners of an object or the pixels that have a really complex and unique neighborhood. Using those interest points we would define a region of interest that can be used to extract unique features.

These features are then stored in a feature vector that can be used to match it to a testing data set that is available in the memory. The goal is to make sure that the blob detected by the algorithm is really a balloon. This algorithm is very robust to point of view of the camera and can be used to find many different interest points. The blobs detected by the color thresholder are used to calculate the density of the interest points that are matched to the testing data. We would take the maximum density of the matched interest points to be the blob that corresponds to the object of interest. After we make sure that the object detected is a balloon, we would enclose a circle to the blob and take the center of the enclosed circle as the location of the balloon. The x-axis location of the balloon is to be used as the input to the third compartment of the algorithm.

The third compartment of the algorithm is the control unit of the robot. The control portion of the code would receive three different inputs that determine the behavior of this compartment of the code. The first input is the distance from the target which is obtained from the ultrasonic sensor located on the vehicle. The second input is the signal generated by the NIR obstacle avoidance module that is used to warn the system of any obstacles that are located in front of the vehicle. The third and last input to the control unit of the code is the location of the object in x-direction that is provided by the image processing algorithm.

The functionality of the control system starts when it receives a number from the detection portion of the code. Then using the ultrasonic sensor, it will calculate the distance from the target. While the distance is not less than or equal to the minimum distance, it will keep moving forward. If the obstacle detection sensor sends a signal to the Raspberry Pi, the code must check to see if the obstacle is not the object of interest, if it is not, it must move backward for 12 inches, turn 45 degrees to the right, move forward for 12 inches, turn 45 degrees to the left, move forward for 24 inches, and rerun the object detection algorithm to find the center of the target again. Using the center of the target, the robot must keep turning to the correct direction until the center of the object is within some limits of the center pixel of the camera.

4.3.3 Algorithm Sensitivity to Operating Environment

This algorithm is very dependent on the environment it is being used in. there are some parameters that are defined in the code that are very dependent on the illumination sources that are used to reflect the objects into the camera lens. Hence, when designing these numbers for a new environment, we must test and calibrate these value in that environment so that we are sure they would respond with the same accuracy to the new environment. In order to do that, we added another feature to our program that allows the user play with the Hue, Saturation, and the Value of the ranges defined in the color filter. This can ensure that our robot will not ramble around without a purpose.

4.3.4 User-Based Interrupts

We must be sure that when the robot is in operating mode, there will not be any sort of false alarms in the detection of these balloons. We are using a very powerful laser gun that may be disastrous if it is shot at a person sitting in the operating environment of the robot. Therefore, it is important to design an interrupt capability that enables the master computer to take full control of the robot in uncertain situations. Sometimes, under special circumstances, these feature matching algorithms would match features that are not correct. When that happens, we must make sure that it does not harm any human being sitting in the crowd. This user based interrupt can be designed in such a way that the robot can be controlled using the pointing keys on the keyboard of a general-purpose computer.

4.4 Microprocessors (MPU)

One of the important aspect of any smart/intelligent system is the brain of the system. In our project, we have many different options that can be used as the central computing unit of a robot. This microcomputer must be capable of performing simple computations for the purpose of detection of any balloon with a specific color. In this project, we will be using one microcomputer to perform the computation required. The imagery data is sent to the computer module, and from there, the computer will execute the detection algorithm to find the object of interest. When the object is found, the control is passed to the control unit of the vehicle, and at that point, the vehicle control unit and the microcontroller module will be communicating with each other constantly.

4.4.1 Microcomputer Options

There are many different microcomputers available off the shelves that can satisfy our project specifications. When choosing a microcomputer, we must take into account the processing speed, number of GPIOs, Random Access Memory space, and compatible peripherals such as camera modules, and range meters that can be connected to the computer module. These factors will be discussed in details later on. For this project, we have considered four possible Single Board Computer Systems.

4.4.1.1 Raspberry Pi 3 Computer Board

This is the third generation of Raspberry Pi. This module contains a BCM2837 processor. Raspberry Pi 3 in *Figure 20* is equipped with 1GB of LPDDR2 Random Access Memory and a 4GB eMMC flash memory. BCM2837 processor is a revolutionary design that incorporated the ARM CPU complex with a Quad Core Cortex A53. This design has a 512KB of Level 2 cache which provides enough power and speed to do real time processing. One cool feature of Raspberry Pi 3 is the fact that all the input/output interfaces and peripherals are fully compatible with the peripherals design for older versions of the module. Raspberry Pi 3 is really small (as small as a credit card width and height), which makes it perfect candidate for our project. The features that standout in Raspberry pi 3 are Low Cost, Low Power Consumption, Reliability, and size. Raspberry Pi has its own development environment known as Raspbian with a lot of well documented libraries for both C/C++ and python programming languages.

FIGURE 20- RASPBERRY PI 3 ©

4.4.1.2 Raspberry Pi Pro Computer Board

This module (*Figure 21)* is equipped with a 1GHz A20 ARM Cortex -A7 Dual-Core CPU. Banana PI Pro has 1GB of DDR3 Random Access Memory Space, and it is equipped with a Graphical Processing Unit. This Module comes with a 10/100/1000 Ethernet RJ45 and is compatible with an optional WIFI module. The size of the module is comparable to a credit card which makes it an ideal selection for out project.

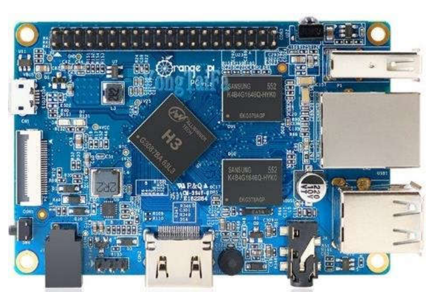

FIGURE 21-RASPBERRY PI PRO ©

This computer board is also equipped with an integrated 802.11n wireless LAN and Bluetooth 4.1. we can use the wireless connectivity for communication purposes with a host computer. a parallel 8-bit camera interface is also included on the board for fast transfer of imagery data. The only issue that this module has is the fact that it is not as popular as Raspberry Pi modules. Therefore, it is very difficult to find technical supports from forums when programming the module.

4.4.1.3 RoBoard RB-100 Single Board Computer

This is a Single Board Computer System that is Specifically designed for Robotic Projects (*Figure 22*). The design of the chip is based on the Vortex86Dx, which is a 32bit x86 CPU with a speed of 1Ghz and a DRAM of 256MB. The Hardware is only compatible with Linux and DOS and Windows. The RoBoard is equipped with Open Source C/C++ Libraries for input/output functions that may be required for sensors and actuators. This module is very user friendly and allows users to develop PC based applications of robotic systems. The system is fanless and cools down using Heat Sinks.This module is very strong and efficient for robotic implementations. If we decide to use this module we have the advantage to add more capabilities to the design. For instance, we can implement highly computational methods like neural networks and classification trees. The only downside of this device is the fact that it is quite expensive and almost double the size of a raspberry pi kit.

FIGURE 22-ROBOARD © RB-100

This computer system can be used to make our robot more intelligent because of the fact that it has over 200 GPIOs and 8-channels of 10-bit precision Analog to Digital Convertors for sensor implementation. The only issue with the module is the fact that it does not have a WiFi Card implemented on the board; hence, if we wanted to connect to internet wirelessly or maybe wanted to communicate with another Computer System, we would be forced to purchase the WiFi module separately. This would add a lot of unwanted cost to the final project

After researching different Microcontroller development boards, it was time for the team to do an in depth comparison and select our final product. The next sections will go in depth of our selection process.

4.4.2 Microcomputer Comparison

Total of 4 microcomputers were presented in the previous section. When making a choice between these computers we must consider 5 aspects that can help us choose the optimal selection. These aspects are as follows: 1) Cost, 2) Power Consumption, 3) General In/Out Pins, and 4) Memory Capacity

4.4.2.1 Cost

Cost is one of the most important factors that we must consider when purchasing a new microcomputer. Among the four computers that we are considering, the most expensive ones are the RoBorad 100 and 110. *Table 4* provides a summary of the cost of each microcomputer.

RoBoards are the most expensive computer modules compared to the other two. The prices are almost 4 to 5 times more than Raspberry Pi and Banana PI Pro. Purchasing these two modules requires a large capital which might be unreasonable if for instance Rasbpery Pi can perform the tasks as effectively as the other two.

4.4.2.2 Power Consumption

The life of the battery and the amount of power drawn by the computing is another big factor that needs to be analyzed in details. We must make sure that the computer system that we select is highly power efficient and does not exceed the maximum power consumption of our project. One must note that the power consumption of computational devices is highly dependent on the application. For example, if a particular image processing algorithm takes about 10^6 iterations of multiplications and summations, it would probably consume a lot of power when compared to an idle situation. Hence, we must take a careful consideration when designing the algorithm for this particular project.

The amount of power consumed by these devices is not known until a prototype is built and the power consumption is measured using a watt meter. Our assumption is that Raspberry Pi 3 and Banana Pi 3 expend less power compared to the two RoBoard RBs since they have a much weaker processor and a smaller operating voltage and current. The exact power consumed by the microcomputer of choice will be experimented under different situations and usages. We will be running experimental codes with different computational complexity, and we will measure the average power consumed for these tasks. Our plan is to test these modules in the same manner as they are sought to be used in this project.

4.4.2.3 General Input-Output Pins

General Input-Output Pins are used to send commands to different modules in the robot. These pins will be used to read and send data from and to different peripherals of the vehicle. For instance, one pin may be used to read data from ultrasonic sensor on the camera module and the other pin will be used to send a run command to the servo encoder on the vehicle. All of these microcomputers have enough GPIOs that can be used for our projects. Our project needs about 20-25 GPIOs at most, and all these 4 computer modules have more than 30 GPIOs in their configurations. *Table 4* is a summary of GPIO's count and their current capabilities.

The maximum current output from the GPIOs in RoBoard RB computer modules were not provided in the spec. sheet. But, the company claims that these modules can be used to run servos without using a motor driver. One big disadvantage of RoBoard Computer module is the fact that the manufacturer does not provide a good datasheet to its customers.

4.4.2.4 Memory size

Memory size is another big factor that plays a really important role in the performance and capabilities of a computer module. When considering memory capabilities of a computing module we must be mainly concerned with the dynamic RAM. DRAMs are volatile memories that use capacitors to store data. These memories are used to store intermediate values that are outputted and used while running an algorithm. For example, a DRAM may be used to load an image from the camera module and perform some mathematical operations on the image. DRAMs are most commonly used in electronic devices because of their cheap cost and high storage capacity.

For our project, DRAM capacity is very important because of the fact that we will be employing many different image processing/computer vision algorithms on these devices. Each image will be an 8-bit precision array of 512 x 512 numbers which comes down to 265 KBs of dynamic data. We must choose a computer module that can perform these processes in real time. Table 3 is a summary of the memory capacities of these 4 modules. One must note that Raspberry Pi 3 comes with a 512KB of L2 cache register. This cache register may be used to perform the image processing algorithms in a much faster manner. DDR stands for 'Double Rate'

4.4.2.5 MCU Comparison Overview

TABLE 4- MCU OVERALL COMPARISON

Computer	Memory Type and Space	GPIO count	I_MAX (mA)	Cost
Raspberry Pi 3 Computer Board	1 GB of LPDDR2 RAM	45	50	$39.95
Banana PI Pro Computer Board	1 GB of DDR3 RAM	40	50	$47.99
RoBoard RB-100 Single Board Computer	256 MB of DDR2 RAM	200	N/A	$250.00
RoBoard RB-110 Single Board Computer	256 MB of DDR2 RAM	200	N/A	269.99

4.4.3 Final Decision on Microcomputer Selection

After comparing the four microcomputer modules listed above, we decided to use Raspberry Pi 3 Computer Board. Raspberry Pi 3 is the cheapest among all four computer modules, and it has enough capabilities to perform the computations required for this robotic system. Raspberry Pi 3 has enough RAM for processing multiple images at the same time. One big advantage of Raspberry Pi is the fact that it is a complete module. This module comes with 4 USB ports, 1 HDMI, 2 UART, Wi-Fi module, and many more. The operating system on raspberry pi is very user friendly and there are many resources available from different forums that can be helpful when integrating our design ideas. Raspberry Pi 3 is also the cheapest computing Modules among the other three competitors. One of the biggest reasons why we chose raspberry pi 3 was the fact that there are many different sensors available for this device and each sensor comes with a library in both C/C++ and Python. This is very useful in accelerating our developments and testing procedures.

Digital Image processing deals with performing computations over a million pixels around the image; therefore, it is crucial for us to have a computer module that is capable of performing these computations in real time. One of the main characteristics of raspberry pi that made it stand out among the other competitors was the amount of RAM it provides us to play with. 1GB of RAM is more than enough to perform computations of imagery taken from a low to mid quality camera. The second feature of Raspberry Pi that was also very impressive was the CPU speed of this modules. Raspberry Pi clock module is capable of executing instruction at the rate of 1.2 GHz. And lastly the size of this module is the smallest among the other three computing modules. This would give us more room for implementing any additional features to the project

4.5 Image Processing

Image processing is the root of any modern robotic system that is used to make it more intelligent. Digital images are a set of numbers (data) that are stored in arrays inside the memory. Many different mathematical algorithms have been developed by different scientific institutions. Most of these theories are based on statistical relationships that exist among these numbers in the array. Imagery data are captured using highly sensitive sensors that are built to capture light reflections through three main channels. The combination of these channels together would result in the creation of a specific color. These three channels are not continuous based systems. When they capture and measure the reflection of the surrounding, they would digitalize the values so that they can be stored in the memory efficiently. In this section, we would cover the basics of image processing/computer vision algorithms that would be used to develop the software for our project. This section would cover the underlying theories behind color models and how they are used in the image processing community for detection purposes. We would expand our understanding of color filtering in conjunction with mathematical morphology.

4.5.1 Design Objective

Our goal is to use a camera module that is compatible with raspberry pi to acquire our imagery data that are to be processed. In this project, we wish to be able to detect balloons of specific colors and pop them using a laser device. Hence, we must be able to detect colors and balloon like shapes. This problem can be broken down into two parts. Firstly, we need to be able to detect a circular/elliptic shape form the image. Secondly, we must make sure that the color of that circular shape is the color of interest. In order to achieve these two tasks, we must get a good understanding of color fundamentals that will play an essential role in detection of the color of interest.

4.5.2 Useful Color Models

We will analyze two main color models that are used frequently in the image processing and computer vision community; then, we will select the best model that can be used for color detection for our project. Some of these models have been developed based on human's perception of color. Human's based perception of color will be a key factor in designing color-based detectors. The two main color models that will be analyzed are RGB and HSV color models. We will discuss the usefulness of each model and provide a mathematical relationship that can be used to convert from one model to another.

4.5.2.1 RGB Color Model

Color images are formed by the combination of three primary channels Red, Green and Blue (RGB). RGB images are the type of images that are modeled in the three-dimensional Cartesian coordinate. RGB models are great for acquiring the image and displaying it on a screen, but they lack practicality that human eyes have when we interpret color. Hence, for the purpose of color understanding, engineers have developed another color model that is very close to how humans perceive color. This Color model is known as Hue, Saturation, Value (HSV).

4.5.2.2 HSV Color Model

HSV model is the cylindrical representation of RGB color model. Hue is namely the angle that a corresponding point in the cylindrical coordinate makes with respect to the positive x-axis. Saturation on the other hand is the perpendicular distance from the vertical axis. Lastly, Value is the distance along the vertical axis. Figure 1 represents the HSV color space in a pictorial manner. Hue ranges from 0 to 360 degrees. It is the measure of how we humans perceive light in nature. Hue is a model that describes a pure color, i.e. yellow, red, blue, and etc. this beautiful property of Hue enables us to perform masking operations on color images to segment specific colors of interest. Saturation ranges from 0 to 255. It is the measure of the amount of white light that has diluted the pure colors.

HSV Model Project Considerations

In our project, Saturation is an important number that must be chosen carefully when detecting colors because a balloon is a specific color with a range of hue and saturation values that determine the pure color in a range of white color dilution. For instance, if a balloon is green and saturation range is chosen to be very wide i.e. [0 255], we will filter all the green values in an image; therefore, if someone wears a green t-shirt, that person will be chosen as the color of interest. Lastly, Value in HSV model is the average intensity of the three RGB channels. Value may be used to make a sharper filter that is more accurate. Using Hue and Saturation, we will design a range of values such that the filter will only select a specific color of interest. Our goal is to minimize the error in color selection and also reduce the amount of noise generated in the binary mask that is to be used to extract the balloon of specific color. Hence, we will be forced to perform some pre/post processing for perfecting the response of our algorithm. One of the most important aspects of edge and contour detection is the fact that, edge detection is not robust to noise

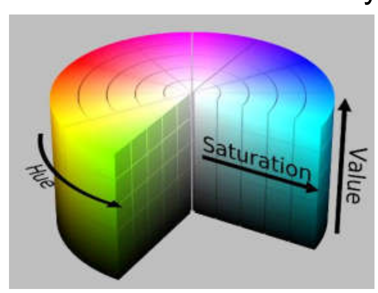

FIGURE 23-HSV COLOR MODEL

included in the image. We can see a three dimensional model of HSV color model in *Figure 23*.

4.5.3 Color Filtering

In this project, we will be filtering 7 different colors; namely, red, green, blue, purple, yellow, black, and white. We will be using the concept of color thresholding by generating a range of HSV values that can be passed through a filter. This is a filtered image of a green balloon taken using the raspberry pi camera module. If we look closer at the bottom right corner of this image, we see that there are some green colors that have been passed that are not considered a balloon. And also, there is a portion of the balloon that is not passed through the filter that we designed. These problems are considered to be noise in the image and we can get rid of them using some morphological processes. This filtered image was generated using a binary mask that was logically ANDed with the original color image. Figure 3 is the binary mask that was used to generated the image in figure 2. Where White color represent the value of 1 and the black color is 0 of the mask.

4.5.4 Morphological Processes

There are two morphological processes that are of interest for this project. These processes handle specific operations in order to eliminate/decrease noise in the image. Slight noise in the image can have extremely damaging effects on the operation of the vehicle. Noise can allow for false target identification and cause the vehicle to stray. The morphological processes we will be implementing in this design to help mitigate erroneous data input are erosion and dilation.

4.5.4.1 Erosion

The first Morphological process is known as Erosion. Erosion is an operation perform on mathematical sets. We can think of Images as a set of numbers in a three-dimensional Euclidean space. Erosion is applied on the binary mask. The resulted binary image will give us the largest consistent blob that is in the image. This property of Erosion makes this operation ideal for reducing the noise contents in the binary images. Therefore, by applying the erosion operation on the mask, we could get a more reliable mask for object detection. The image produced is the result of eroding the binary image. The noise rejection of the filter is achieved, but the size of the balloon mask is also eroded. In order to fix this issue, we will be using another morphological process known as Dilation.

4.5.4.2 Dilation

Dilation is the second morphological process that is used to expand this binary mask to a larger size. The resulting binary mask after performing the dilation operation is given in *Figure 24*. As we can see, the mask has grown in size and it is in the same location as the original balloon.

4.5.5 Edge and Object Detection

After obtaining a blob of the balloon, it is time to find the minimum enclosing circle that can be fitted to that blob. There are three methods we have considered to execute edge detection. One method involves finding the minimum enclosed circle of the specified object. The other method, known as Hough Transform is a heavily computational algorithm designed to find circles in and image. The third method is using SIFT algorithms; the following will be discussed below.

FIGURE 24-MORPHOLOGICAL PROCESS FROM LEFT TO RIGHT

4.5.5.1 Minimum Enclosed Circle Technique

In order to do that, we must first find the contours in that binary mask, and then enclose that contour using the minimum enclosing circle possible. The center of the enclosing circle indicates the location of the balloon. *Figure 25* provides the pictorial explanation of minimum enclosing circle technique. This method is very efficient and fast to implement on raspberry pi since it is not computationally intense.

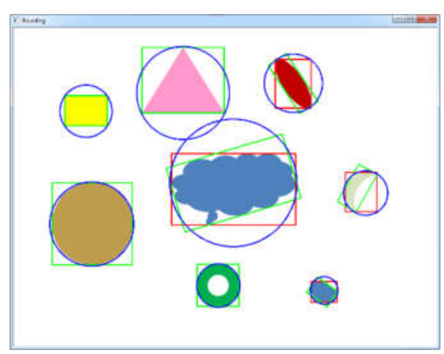

FIGURE 25- MINIMUM ENCLOSED CIRCLE

4.5.5.2 Hough Transformation Technique

Another approach that we could have to this problem involves Circular Hough Transformation. Circular Hough Transformation is technique that can be used to find circles in an image. It is based on the canny edge detector which is itself based on finite difference of pixels. In this approach, we must be careful when handling the images. These images are taken using a low to mid quality camera module that can and will introduce artifacts and noises to the image. Noise may not be observable by a human's eyes but the fast fluctuation in the pixel values are crucial when finding the derivative of an image. Therefore, before we take the Hough transform of the color image, we first change the color to gray-scale. Then, we would have to pass the image through a low pass filter to minimize the noise contents of the image. Our filter of choice is a low pass Gaussian filter of size 15x15. Gaussian filters are great filters because they have a really smooth transition from 1 to 0 in the Fourier domain. This beautiful property of these types of filters makes them ideals for noise removal without any introduction of artifacts in the image.

After taking care of the noise we apply the circular Hough transform to find the circles in the image of interest. As results, we hope that we would get multiple circles in a frame of the video stream. Then we would take these circles and perform color thresholding to make sure that the color of interest is chosen as the target. Hough Transformation is a little bit more computational than Color thresholding and morphological processing. Therefore, we will only choose to implement Hough Transformation, if necessary.

Our goal is to extract the best range of HSV values such that we will have the minimum amount of error in our binary mask, and then, using Erosion and Dilation we would hope to perfect our masking process.

Hough Transformation is a perfect choice for a more powerful module that can execute instruction in a faster manner. If we decided to use Hough Transformation, we will have to decrease the resolution of camera, if needed. One must note that Hough Transformation is a more accurate method of detecting balloons, and it can be used in conjunction with color thresholding to improve the reliability of our algorithm.

4.5.5.3 SIFT Algorithm

Another powerful object detection technique that may be used for our project is known as SIFT algorithm. This algorithm stands for Scale-Invariant Feature Transformation (SIFT). SIFT algorithm needs two images to match objects. It works based on key point extraction from gray scale images. This algorithm is based on scale-space theory developed for one-dimensional signals. SIFT is used to find pixels in an image that are interesting in the sense that they have a unique neighborhood of pixels. For instance, one human's face has some contours that are unique when matching to imagery data from the face. Those contours are located in the neighborhood of the edges that connect the nose to the eyes or the pixels that are on the edge of the lips.

After the detection of interest points, SIFT algorithm defines a vector based on the neighboring pixels that describe the interest point. This vector is known as the feature vector of the descriptor of the interest point. Using the descriptor, we can match same objects in different imagery. SIFT Algorithm has many advantages that make it stand out among other detection algorithms. Some of these features are as follows:

1) SIFT algorithm develops the features that are local in the image. Which means that it can be used to detect many objects, large or small
2) The Features are very distinct; hence, false alarms are reduced when matching the interest points
3) The algorithm performance is independent of noise, change in 3D viewpoint, affine Transformation, and illumination

If considered, we will implement all three methods on the Raspberry Pi module and select the best out of the three.

4.6 Wireless Communications

The Stinger will require confirmation from the operator before annihilating the target. In order to make this as seamless as possible, it is necessary to select and establish a communication protocol between the robot and the control station. There are a handful of options to choose from in this regard. Some solutions may be more extreme insomuch that they are typically used in long range satellite communications, while others are primarily used in devices to transmit and receive data to and from other devices in the immediate vicinity.

4.6.1 Bluetooth

Bluetooth is a form of wireless communication that is becoming more ubiquitous as time passes. It is found in almost every smartphone nowadays and as companies like Apple make the move to cut cords, it is highly likely to become a standard for all external peripherals. The pitfall for this communication protocol is that it only operates within 10 meters or less of range for the most common Class 2 Bluetooth devices. If the extra range is needed, one could opt for a Class 1 device which transmits at a power of 100mW and has ten times the range at 100 meters. Bluetooth operates on a frequency of 2.4GHz which happens to be the same as WiFi. This means that an external antenna could be attached to a Class 1 device and the range can be magnified exponentially. While this may seem like a viable option for keeping up with the fast-paced evolution of technology, Class

1 devices with SMA connectors are not readily available and would require some modification to achieve the desired range.

4.6.2 WiFi

WiFi is found in almost every household nowadays and provides a wireless link between the modem and the terminals around the house. This allows the users of said terminals to gain access to the internet as well as to communicate with each other over the network. WiFi operates on two frequencies independently of each other. Older devices use 2.4GHz while new devices such as tablets and smartphones will connect using 5GHz. As can be demonstrated by the applications for home networking, the range of WiFi technology is a benefit to its usability. Similar to the Class 1 Bluetooth modules, there have been modifications to WiFi routers that allow for transmission and receiving of signals originating miles away from the router. The availability of such devices and their ease of setup makes this a sound choice for a communication protocol on the Stinger.

4.6.3 RFID

RFID is a type of communication where an electromagnetic pulse from a reader provides enough power to activate an embedded chip on the device. This chip, once powered, will send the information stored on that chip to the reader and then will power down. This is typically a very close range type of communication and will not be of much use for this particular application.

4.6.4 GSM/CDMA

Both GSM and CDMA are mainly used for mobile phone communications. There have been several applications of GSM in robotic communication however. The fact that the device can connect to the cell towers allows it to communicate with virtually any device that also has a cellular connection and also anywhere around the world. The limitation with the technology is that in enclosed spaces such as buildings or tunnels, the signal is either degraded or lost entirely. This is not so great for a robot that relies on human confirmation for target elimination.

4.6.4.1 Wireless Communication Comparison Overview

Wireless Communication	Frequency	Distance	Power Output
Bluetooth (Class II)	2.4 to 2.485 GHz	10m (typical)	2.5mW
WiFi	2.4 GHz, 5 GHz	100m	100mW
UHF RFID	300 MHz to 3 GHz	12m	1W
GSM/CDMA (class I)	380 MHz to 900 MHz	35km	1W

4.6.5 Final Decision on Communications

Because of the availability of WiFi communication on the RPi and the relatively low cost, we opted to go with a WiFi router connected to the control station. This router will be configured with a static IP address allowing the RPi to connect to that access point. WiFi has been and is continuing to be one of the top technologies in wireless communications. Wireless communication is available anywhere on campus which will allow the Stinger autonomous vehicle to travel unrestricted.

4.7 Final Part Selection

In the figure below, our design team has laid out the major components involved in our project. All of the surface mount components have been installed onto breakout boards for future breadboard testing

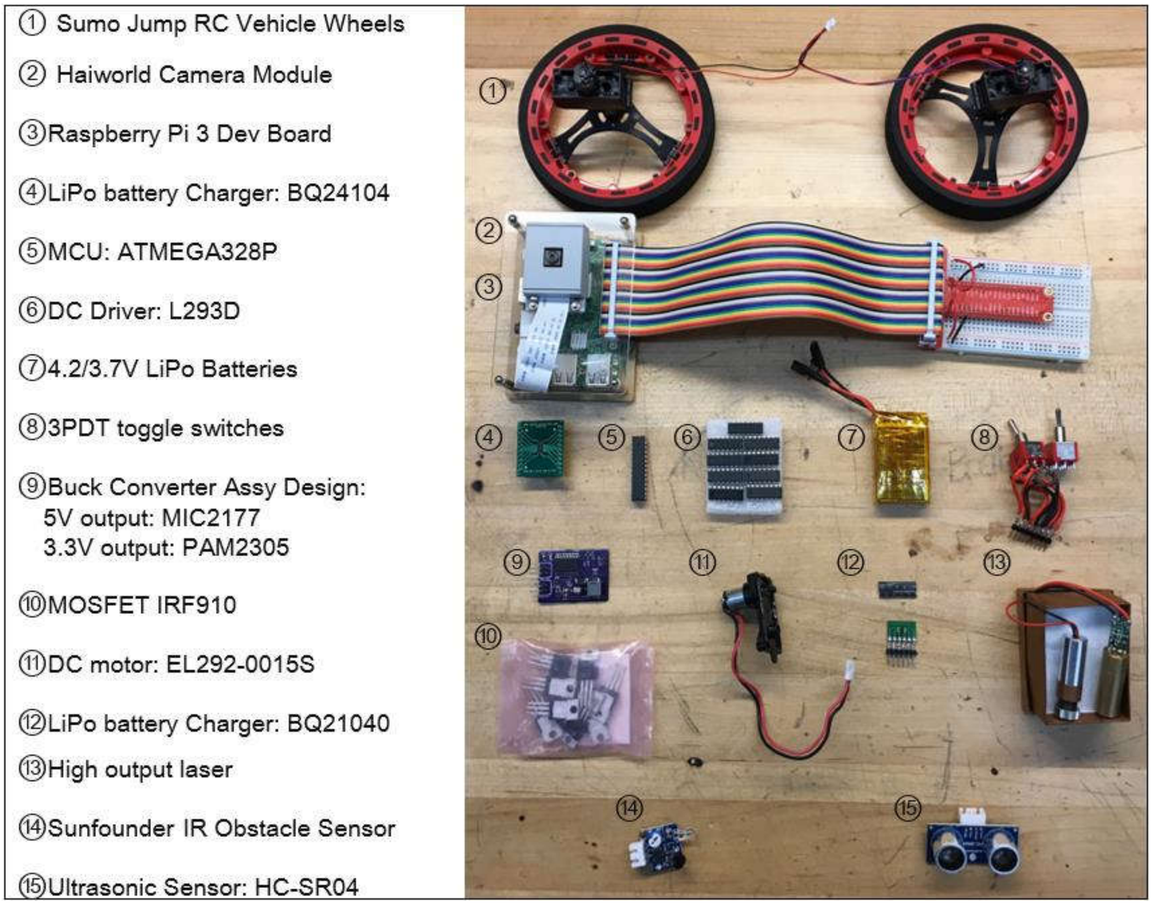

FIGURE 26-FINAL PART SELECTION LAYOUT

5 Design and Implementation

In this section we work through our initial testing and developmental processes all the way up to our final product design. This section captures the electrical testing, configuration, and integration of multiple systems/components. The software development is provided in this section, which we will walk through the morphological processing of achieving image detection. Lastly, in section will include all of the final system designs and schematics.

5.1 Electrical

In this section shows the various developmental stages following the research phase of this project. Initial testing is done on the major components selected, to include the battery management system, control system, and laser actuation. Images in this section are from actual testing and design process on the successes achieved thus far.

5.1.1 BMS Components and Design

The following section details the design and testing of the battery management system. Operation of the BMS requires the charge controller integrated circuit, reverse current flow protection, charge status indication, charge/discharge switching unit, and device interface.

5.1.1.1 Charge Management IC Chips

The battery management system will use a Li-Polymer Charge Management Controller. This microchip is embedded with the necessary circuit/battery protection hardware we will need to guarantee safe operation of the remote control vehicle and user during charge and discharge operations. The microchips are embedded with charging algorithms that will achieve optimal capacity and safety in the shortest charging time possible. Outsourcing these compact microchips will not only help in the function of our design project; it will also heavily reduce cost, weight, space required by fabricating and designing the internal circuitry that is packed into these powerful charge management chips. Several LiPo charge management controllers were investigated during our research. The top three controllers were purchased for further testing and evaluation for the final product. Three manufacturers were chosen; Microchip, Texas Instruments, and NXP. This section is an overview description of the hardware features, functions, and capabilities.

Li-Pol BCMC Hardware Selection

For our project, we have chosen to use Texas Instruments single cell Li-Ion/Pol Battery Charge Management Controller (Li-Po BCMC). The controller offers up many of the safety functions and operating parameters as its competitors, to include voltage regulation, high input voltage acceptance, rate of charge, small form factor for limited space, and charge status indication. However, the Li-Po BCMC has added protection with the additional temperature-sensing terminal. This terminal will ensure that the battery does not overheat during charging. If so, the current to the battery is limited from the embedded circuitry. In addition, Texas Instruments beats out its competitors in pricing and capability of low quantity orders.

5.1.1.2 Reverse Current Flow Protection

In addition to the charge management controller microchips, the battery management system will be equipped with diodes to prevent reverse current flow. Battery reversal can be fatal to portable equipment. Battery-operated equipment is prone to the consequences of batteries installed backward, accidental short circuits, and other types of careless use. The effects of a reversed battery are critical. Unfortunately, it is difficult to guard against this situation without additional cost to the manufacturer. [4] One simple solution to prevent reverse polarity from incorrect battery installation is to use a diode in series with the supply. However, this renders the device inoperable if the battery is incorrectly installed. Another approach is a standard H-bridge circuit. This is costly due to the increased hardware (diodes), but it is extremely effective and makes the circuity polarity independent. Another effective but costly solution is the use of 2-pin JST connectors. The JST connector are designed so that the user cannot mistakenly plug in the battery incorrectly. This JST connectors increase the cost; however, it gives the added benefit of a plug-and-play design. JST connectors eliminate the use of soldering for removal/replace of the battery source.

5.1.1.3 Charge Status Indicator

The battery management system needs a means to communicate with the user for state of charge, battery level, and so on. Different methods are used to in order to convey this information to the user. LCD screens can convey a large amount of information directly to the user, but drives up the cost. A simple cost efficient approach is the use of color LED's. LED's not only lower the cost of the system, but also the engineering complexity. In our design, we will use LED's to indicate the status of the battery, such as: when the battery is charging, when the battery is charged, and when the battery has dropped below a specified threshold voltage.

5.1.1.4 Charge/Discharge Switching Unit

Higher voltage demands in our project, such as the Raspberry Pi which runs off of 5VDC/2A source and the DC motor assemblies which may require voltages as great as ±7VDC cannot be satisfied through a single cell Lithium Polymer battery. Two approaches were considered in our design to satisfy this higher voltage requirement. One option was to design a circuit capable of boosting the voltage of the 3.7 single cell battery. This could satisfy the power consumption required by the Raspberry Pi; however, with the entire integrated system running, coupled with the consumption required to run the motors, this did not seem like a reliable engineering design choice. Rather than catering to a single cell power source, our end decision lead us to option two. Which was to include a secondary Lithium-Polymer cell. By wiring the two in series, we can obtain twice the voltage. There is a problem that occurs when introducing a second battery to the existing system, however. Batteries wired in series will not charge proportionally with a single charging system. A series circuit may result in the overcharging of one battery, and the undercharging of the other. This imbalance has potentially dangerous results that can cause a battery to catch fire, or cause the system to function improperly.

The solution to balanced charge/discharge operations is a power supply switching system. After some research, a rather simple solution was considered and chosen. In order to maintain balance charging of the batteries, the charging unit would need to charge the batteries in parallel. This would allow for the voltage level to be equal across both sources. As for the charging circuit, when the batteries are in parallel, the circuit recognizes it as a single battery except with a higher capacity. The other state of the power supply switching system would allow for the batteries to be wired in series. When wired in series, the batteries are no longer being charged by the charging system and are instead wired to the load. Now, the load is supplied with 7.4VDC, thus satisfying the power supply of both the Raspberry Pi and other heavy loads like the motors and laser. In our design, we used a triple-pole double throw switch, to allow for series and parallel wiring of the batteries.

5.1.1.5 Charging Device Interface

Another consideration when designing the battery management system is the type of connection mechanism used for the charging port. Barrel jacks are a popular design; however, they typically are built as one solid unit (i.e. AC/DC converter permanently tethered to the barrel jack), and vary in size. This has hindered their popularity amongst consumers. For this reason, our design steers towards universal serial bus (USB) adapters.

5.1.1.6 Battery Management System Schematic

The schematic below shows our BMS design for the charging and discharging of the Li-Po batteries.

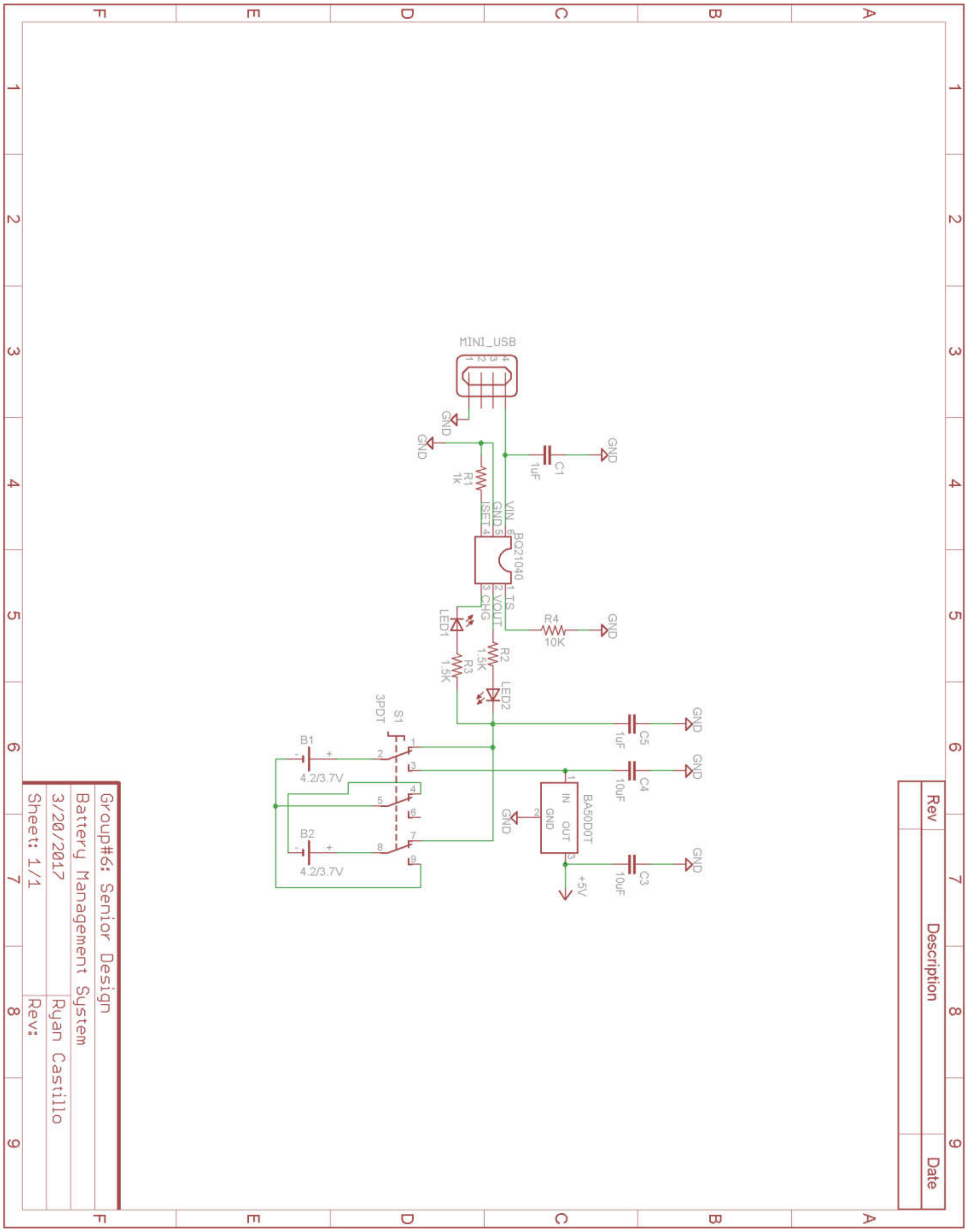

FIGURE 27-BATTERY MANAGEMENT SYSTEM

5.1.2 Component Integration (Breadboarding)

In the figure below the team did a full system checkout by breadboard. The 3PDT switch in the top right corner of the board controls the charge/discharge operation of the batteries in the bottom right. The BMC can be seen on the top left side of the board. A single motor was installed and operated through PWM signals provided the ATMEGA328P. The laser was actuated through a MOSFET switching circuit; which control signal was provided via the Raspberry Pi through software.

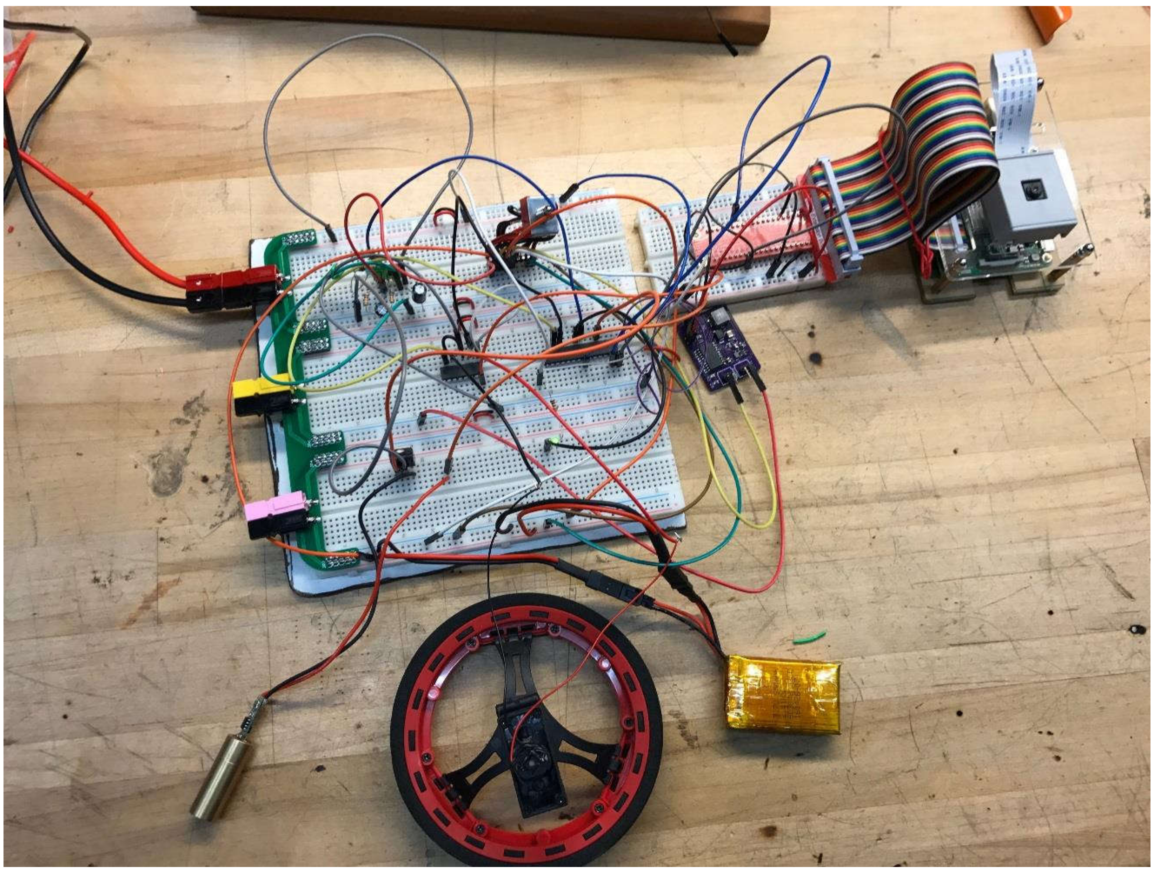

FIGURE 28- STINGER AV COMPLETE SYSTEM BREADBOARD CHECKOUT

5.1.2.1 Battery Management System

The team constructed the BMS electrical system. The preliminary testing used a linear voltage regulator to provide a constant 5V power supply to the Raspberry Pi, and a capability of up to 2A of current. However, the linear voltage regulator has been replaced with a buck converter for power efficiency. The 5V voltage regulator will still be used in another area of the circuit, to provide the laser drive with constant voltage.

The system performed as advertised, providing the batteries with 500 milliamps of current when charging. The illumination of the green LED indicates the batteries are in the charging configuration, which is manually done by the toggle switch. When the batteries are sufficiently charged (approx. 8.2-8.4V) the IC removes current from the system and the current output drops to zero.

5.1.2.2 Buck Converter Integration

Buck converters allow a constant/stable voltage power supply and use less power through switching circuitry. The team has designed a single PCB with 5V and 3.3V buck converters to power the MCU and Raspberry Pi seen in the figure below.

5.1.2.3 Laser Diode Testing

The three lasers were individually tested for power output using a laser power meter. The lasers were used in different parts of development. The high power laser was used to test functionality, and also verify integration compatibility. The low power lasers were used for any additional testing or development. The testing of the laser powered by two 3.7V/ 650mah Lipo batteries was accomplished by the design team. When hooked up to the power supply, the laser drew 880 milliamps at 8.0VDC. 8VDC was used to simulate batteries at roughly full charge. The laser requires a constant voltage source of at least 5VDC; however, the driver will vary the current needed in order to power the laser. Therefore, the source should be able to supply at lease an amp of current. The LED emits a bright ultra-violet beam of light. The power output of this is almost a half a watt of energy. The laser is equipped with a G2 lens which allows to focus the beam; thus, concentrating the energy density. When the beam is focused, a high concentration of energy is transferred from light to heat, giving it the ability to pop a balloon.

5.1.2.4 Stinger Autonomous Robot Design Schematic

Below is the complete Stinger autonomous vehicle schematic.

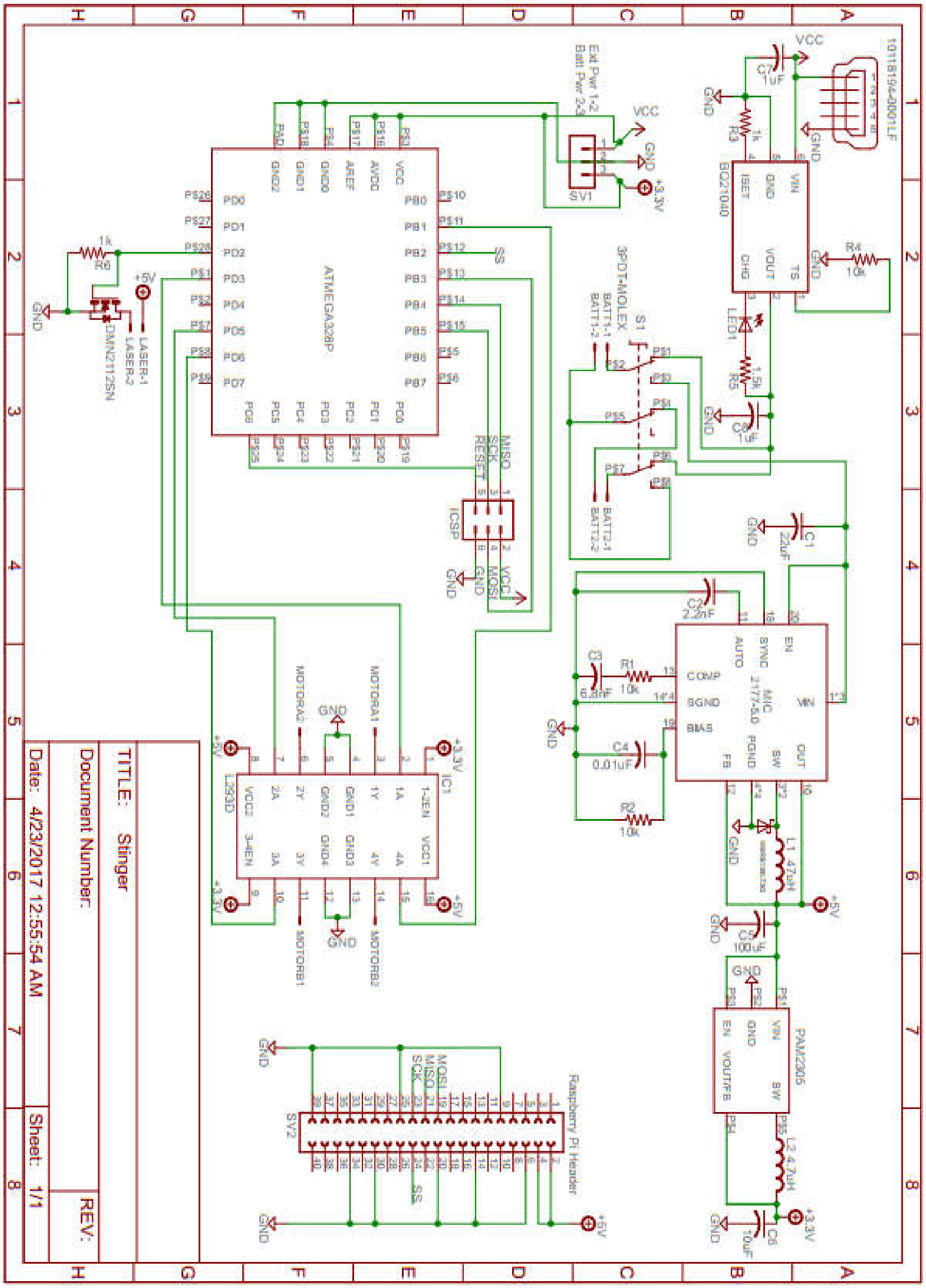

FIGURE 29-STINGER AV COMPLETE SYSTEM SCHEMATIC

5.2 Software

The implementation of software was mainly focused on the image processing algorithm which was divided into three main parts. When an image is obtained from Raspberry Pi camera module, it is stored in the RAM of the module as a color RGB model that has three main directions. This color model is transformed into the HSV domain using some mathematical operations. HSV domain is then used to detect the color of interest using an operation known as color thresholding. Using the color Threshold, we can generate a mask that can then be used to extract a color. Lastly, we perform some form of analysis that helps us make sure that the object detected is the object of interest. A low level description of all three parts of this implementation is given in the following sections. For the purpose of demonstration, we will be using the following image which was obtained from RPi camera module to explain all the parts of this algorithm.

FIGURE 30-SINGLE FRAME IMAGE PRIOR TO FILTERING

5.2.1 Color Model Transformation

HSV domain is known as the Color Perception model because it is very similar to the way humans perceive an image. HSV , RGB, CMY, and etc. are all different color models that are used for different applications. These three dimensional models represent an image using different three dimensional functions that are depicted in *Figure 31*. Hence, one can extract different types of information from each color model.

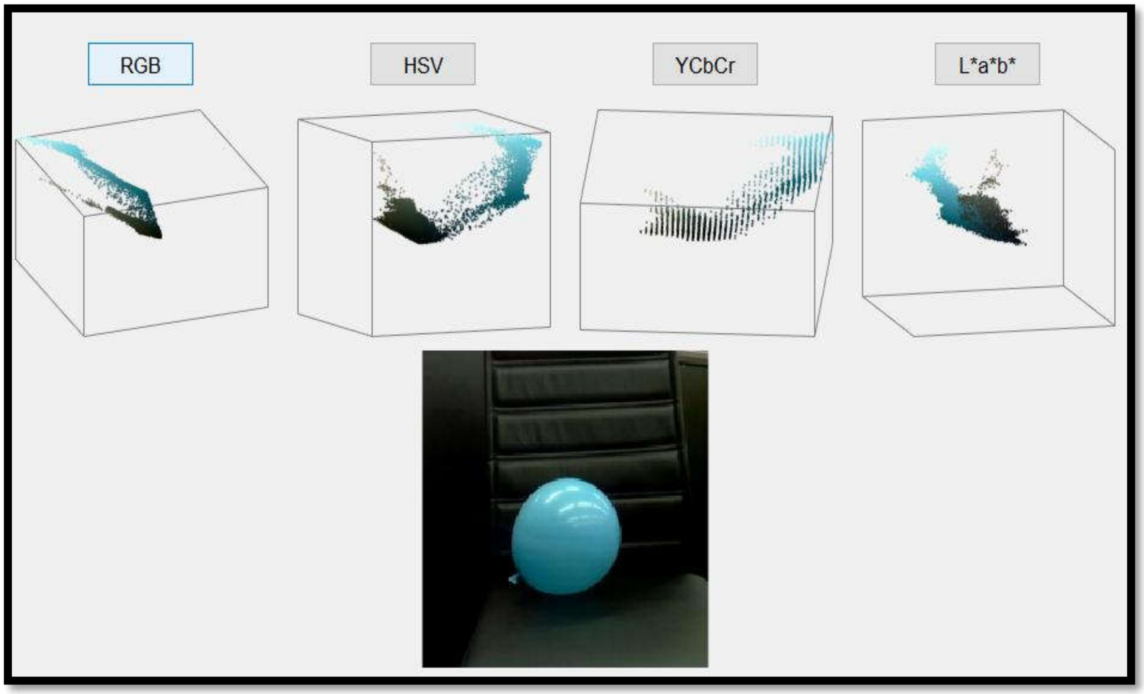

FIGURE 31-PRIOR TO IMPLEMENTING HSV TRANSFORM

In this project we extract the RBG model that is highlighted in blue and we transform it to HSV using the equations shown below.

EQUATION 2-HSV TRANSFORM EQUATIONS

$$M = max\{r, g, b\}$$
$$m = min\{r, g, b\}$$
$$c = M - m$$
$$v = M$$
$$h = \begin{cases} (\frac{g-b}{c} mod 6) * 60 & r = M, c \neq 0 \\ (\frac{b-r}{c} + 2) * 60 & g = M, c \neq 0 \\ (\frac{r-g}{c} + 4) * 60 & b = m, c \neq 0 \\ 0 & c = 0 \end{cases}$$
$$s = \frac{c}{v}$$

- '**M**' is the set of maximum values contained inside the set of r,g,b values.
- '**m**' is the set of minimum values contained inside the set of r,g,b values.
- '**c**' is the chroma, which is the difference between the maximum and minimum.
- '**h**' is the hue value which is a function of h(r,g,b,c).
- '**s**' is the saturation value, which is a function of s(c,v).

HSV domain image is not very pleasing for the purpose of display, but it contains very important information with regards to the color contents of the image. The HSV domain Transformation of the image is shown in *Figure 32*. As we can see, the balloon is in a sense extracted from the background. After the transformation is complete, we are to separate the three color spaces and applying a threshold that can be used to extract the color of interest. In this part of the project our main goal is to limit the Hue and Saturation values of the image to a certain bound that represents the color blue or any other color of interest.

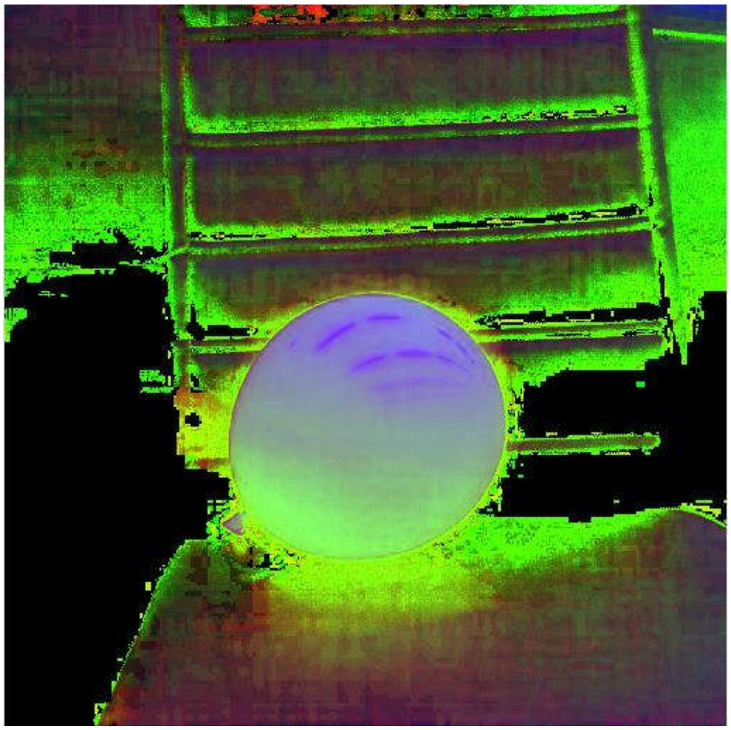

FIGURE 32-AFTER HSV TRANSFORMATION

5.2.2 Color Thresholding

Color Thresholding is a very simple way to segment an image into different objects in color image processing. This technique is mainly used to create a binary mask based on the color image. This method is broken down into 2 main parts that affect the performance of the thresholder.

The first part deals with defining the range of interest that is believed to be the range corresponding to the color of interest. This part is mainly experimental and is very dependent on the environment of the robot. Therefore, we have implemented a graphical user interface that can be used to tune the ranges of Hue, Saturation, and Value of the thresholder so that if we change the environment of the robot, we can adjust these ranges accordingly. *Figure 33* is the result of thresholding the image by limiting the bandwidth of the Hue component of the image. As we can see, some parts of the balloon have been decomposed and eroded away by using the thresholder. This is because of the fact that the surface of the balloon is very reflecting when exposed to white light; hence, some parts of the balloon is seemed to be non-blue color to the computer. This is not going to be a problem as long as we eliminate the noise in the mask that was used to generate the image in *Figure 33*. If we take a look at *Figure 33* which represents the binary mask used to extract blue color, we see that there are a few white dots that may confuse the robot when detecting blue color. In order to get rid of these noises we will be using the two morphological processes.

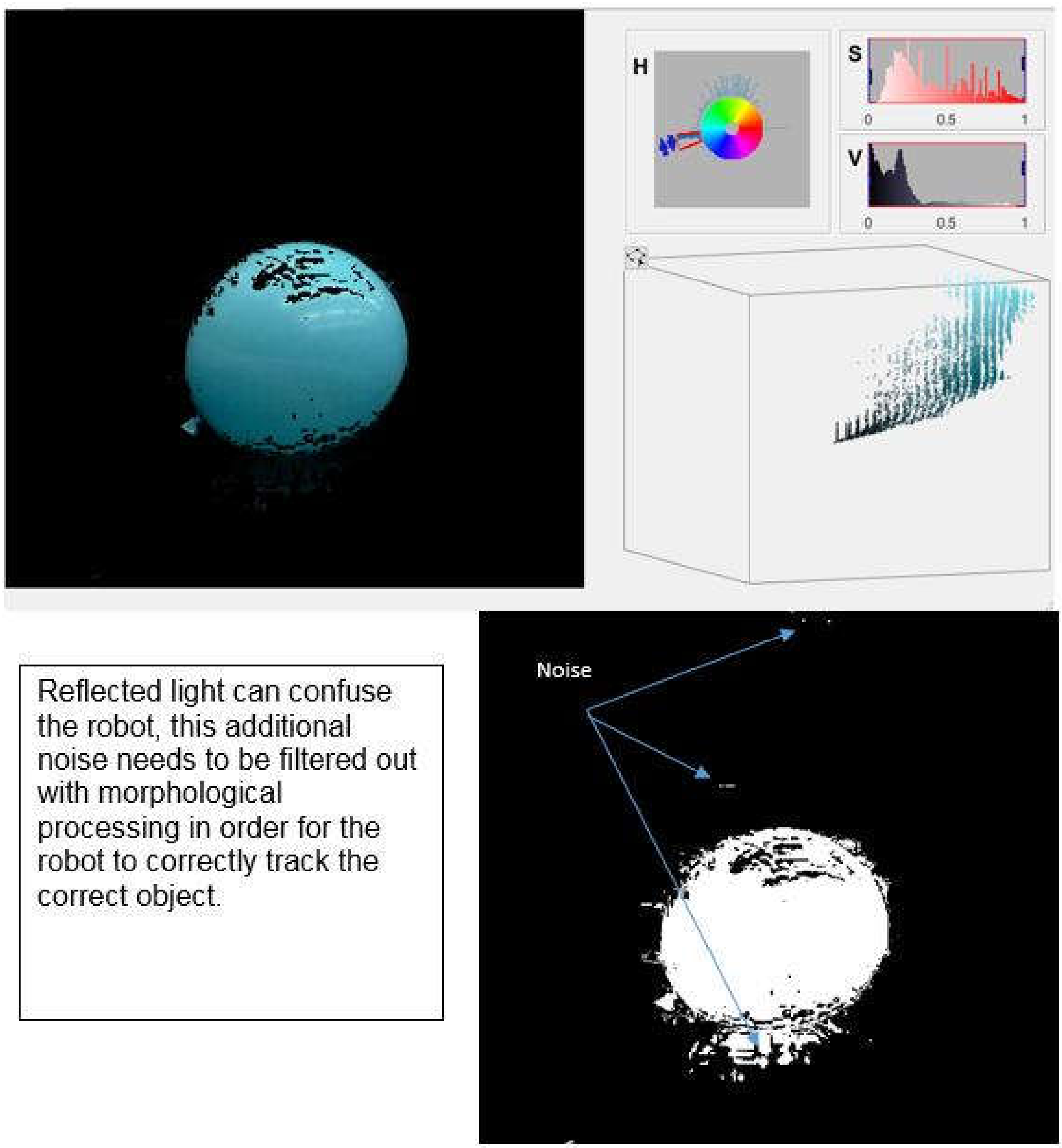

FIGURE 33-NOISE ELIMINATION USING MORPHOLOGICAL PROCESSING

5.2.2.1 Erosion and Dilation

Erosion and dilation techniques were used in order to decrease noise and erroneous data input from the image, the method and application was applied in our testing and described in the following paragraphs below.

Erosion:

The second part of the algorithm deals with the use of erosion and dilation in perfecting the binary mask generated by color thresholding. In order to get rid of the noise in the binary mask we first need to erode the image using a convolution mask that is circular. It is important that the erosion mask is circular because we would like to keep the structure of the binary image which is circular in nature. By performing the erosion we would cause the mask to get smaller in size, and we would destroy the noises in the mask. *Figure 34* is the results of the erosion applied using an 11x11 size mask. As seen from the image in figure 6, bubble like features are introduced to the mask that are not ideal for the performance of the algorithm. We would need to perform the opposite action to get rid of these bubble like features by performing the opposite morphological process known as dilation. When performing the dilation process, it is essential that we use the same kernel as the one used for erosion. This is because we would like to minimize the decomposition of the size of the mask as much as possible.

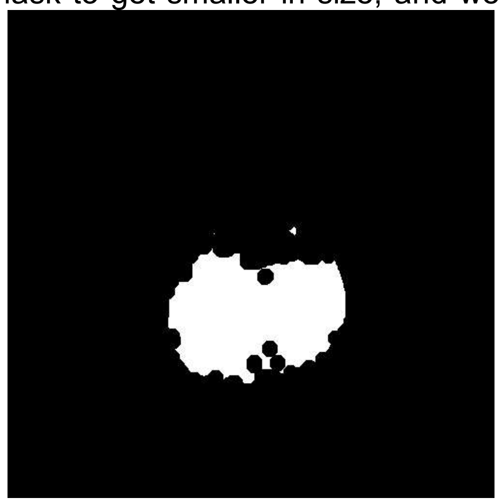

FIGURE 34- AFTER EROSION

Dilation:

Dilation is mainly used for two reasons. One is to get back a mask that is approximately the same size as the balloon of interest. The second purpose of Dilation is connect components that are close together. If we take a look at *Figure 35*, we realize that there is a small white dot that is considered part of the balloon. Ideally, we would like to connect that region to the larger blob that is used to detect the balloon. Figure 7 is the result of the dilation process of the image shown in *Figure 35*. As we can see, we have achieved our goal to connect the components that are considered the same object. Using this binary mask we can generate a minimum enclosing circle that is used to find the

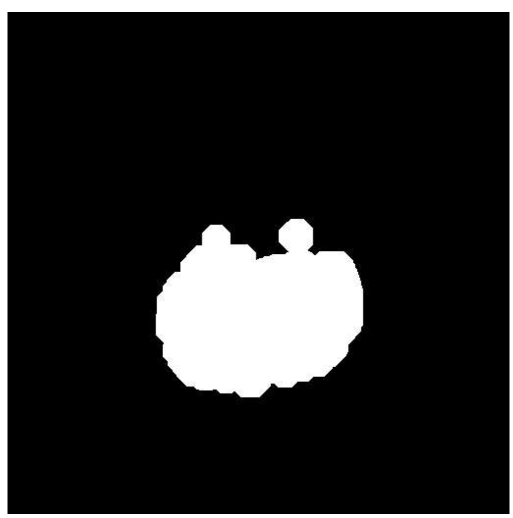

FIGURE 35- AFTER DILATION

center of the balloon of interest. In order to make sure that this circle is the balloon of interest, we perform some feature-based and area based tests that are explained in the validation section.

5.2.3 Validation

Color-Based detection is a very useful tool when performing detection of color only. In this project our main goal is to detect balloons which are mainly circular. If we just use the color Thresholder to detect a blue balloon, our robot might detect a color that is blue as the object of interest and attack that object. Therefore, it is important that we make sure that the blue object is definitely a balloon. In order to do that, we first implemented an algorithm developed by David Lowe known as SIFT with the help of OpenCV. We were hoping that SIFT can help us detect some interest points that are very distinct that can be used to describe a balloon using a set of feature vectors. Unfortunately, SIFT detector did not work out as expected. One reason why this algorithm failed was the fact that a balloon is a very simple object that is not very distinct in nature; hence, it is very difficult to find points that are distinct in a frame. Failure of SIFT algorithm led us to use a simpler method that we call area-based Validation.

Area-based Validation is a very simple method that can be used to measure the confidence of the detection using a ratio of areas. When a binary mask is obtained and processed, we would use it to find a minimum radius enclosing circle that is used to enclose the mask using contours. This circle has a radius that can be used to calculate the area of the circle. The area of the circle is the known as the Assumed area of the balloon $A_{assumed}$. The basic theory is that $A_{assumed}$ is larger than the area of the mask generated from the thresholder.

The area of the binary mask can be easily obtained by counting the number of non-zero pixels in the mask. The area of the mask is denoted by A_{mask}. In order to calculate the confidence of our detection we would have to find the different between the two areas. This difference is denoted by $A_d = A_{assumed} - A_{mask}$. A_d is then used to find the ratio of the enclosing circle area that is not included in the mask. This ratio is denoted by r which is given by $Ad/A_{assumed}$ is used to measure the confidence of our detection. Hence the measure of confidence is obtain by subtracting r from the value of 1. This measure of confidence is denoted by c, and if c > 0.8 we are sure that the object that is detected is a balloon.

EQUATION 3-AREA DIFFERENCE OF THE MASK

$$A_d = A_{assumed} - A_{mask}$$

5.1 Control System

The control system of Stinger is designed in conjunction with the image processing algorithm. The detection phase of the robot is based on the image processing system, and as soon as the object of interest is detected the code moves into the control phase. The robot is driven by two DC motors that are controlled by a driver module. L293D is the driver module we are using to drive these two DC motors. The control unit works based on 4 main signals that are sent via Raspberry Pi. These three signals are responsible to turn the PWMs on 4 channels on atmega328p microcontroller. *Table 5* provides a summary of the 4 main signals and the responses at the four main pins responsible for PWM generation

TABLE 5-L293 SIGNAL RESPONSE TABLE

Direction	PWM1	PWM2	PWM3	PWM4	Binary Code
Forward	On	Off	On	Off	1010
Backward	Off	On	Off	On	0101
Left	On	Off	Off	On	1001
Right	Off	On	On	Off	0110

The control unit would be receiving 5 different numbers that indicate the type of motion that is to be executed by the controller. 4 of those signals are listed above which are 5,6,9, and 10. These numbers are based on the binary values tabulated above. The last number can be anything less than 8 other than those 4 numbers listed above. Last number is an indicator that the robot needs to be stationary. This command will be sent to the control unit if the robot has reached its destination and is ready to shoot down the target of interest.

In the implementation of the control unit, we will be using L293D to drive the DC motors. This driver is consisted of 16 different pins that are used to control the speed of two motors. One amazing feature that L293D has is the fact that it has clamping diodes implemented in the chip internally. The clamping diode are used to protect the chip from the transient response of the inductive load/the motors.

5.1.1 Control Unit flowchart

That figure below shows the actual software control flow developed by our team of engineers.

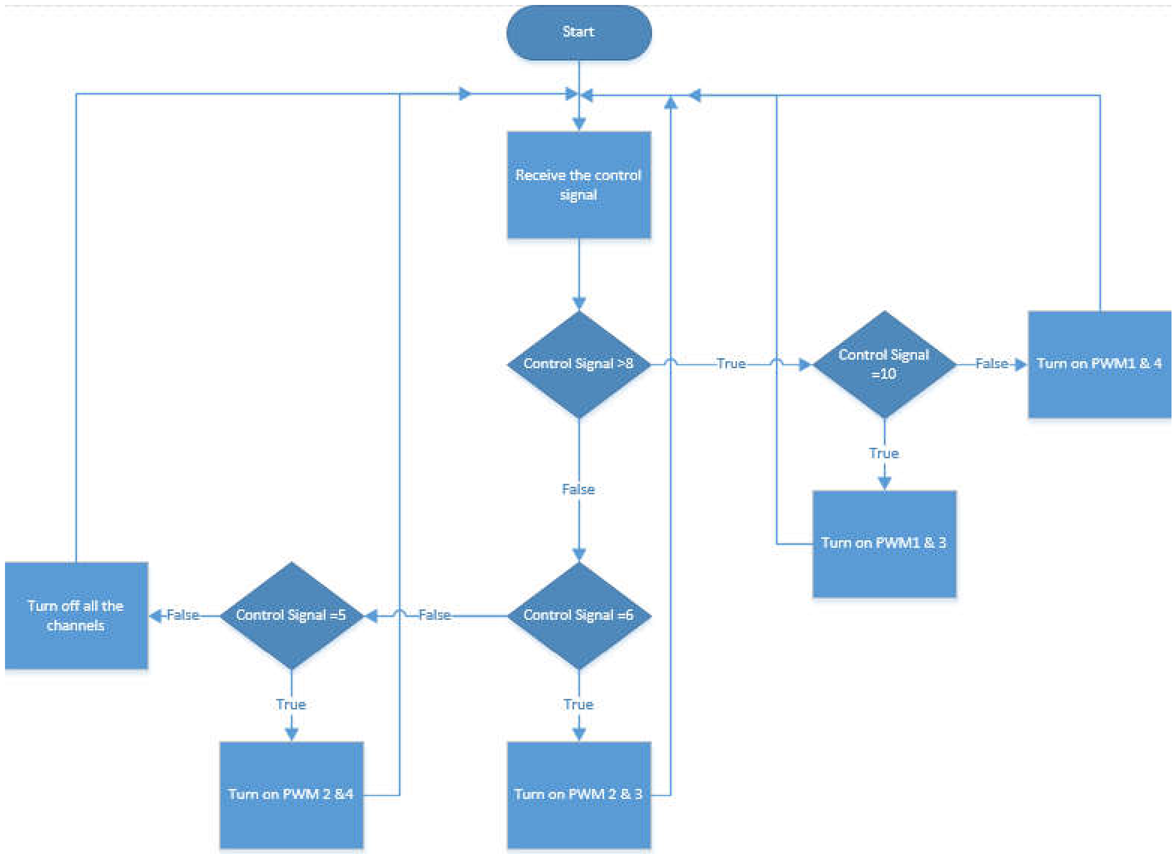

FIGURE 36-STINGER AV CONTROL UNIT FLOW CHART

6 Administrative Duty

This section contains the management portion of the project. It will first show and discuss the project milestones in progressive order for the team. Next, it will examine the projected cost/budget analysis of the project.

6.1 Project Milestones

This is a really challenging project which incorporates different fields of engineering disciplines. We decided to breakdown this project into 4 main parts as follows:

- **Research**
- **Development**
- **Implementation**
- **Prototype and Test**

Our goal is to finish the first three parts of our project by the end of this semester so that we have all the knowledge and tools to prototype our design and test every component/module in the design. Every part mentioned above is fully explained in the following numbered items:

6.1.1 Research

The first part of our project is the most valuable part of the design effort. This Research will help us prepare our final report paper by providing us the advance engineering theories behind different parts of our project. The research can be broken down into 5 main categories. The first category is the operation of the battery management system. We need to research and determine what type and size of battery we will need for optimal functionality. The battery charging station should be capable of docking multiple batteries at once.

The second part of the research deals with the development of the image processing and camera integration. The algorithm is used to detect the object of interest. We want to use python programming language to develop our detection, tracking, and command control. We will have to familiarize ourselves with python, especially OpenCV library and its functions. Image processing portion must be done carefully since our hardware is not as powerful as a general-purpose computer system that we have at home. The image processing must be simple enough to avoid latency issues and cause the vehicle to respond erratically.

The third part of our design deals with controlling the robot. The control portion works based on the signals received by the main computer system of the robot. The control system will manipulate the movement of the robot. The robot is steered through voltage signals received from the GPIO; therefore, we will need to spend a significant portion of time developing a system that is capable of coordinated turns and precision movements.

The fourth part of the design is the PCB development. We will have to learn the fundamental rules for designing circuit boards on a development environment to make sure that our components operate smoothly and without any problem. The last part of the design is concerned with the communication system. We will have to learn ways to interface different processing hardware. Since this project is a modular type system, we must make sure that each module is following the same communication protocol.

6.1.2 Development

The development portion of the project is the part that we use our knowledge, attained from the research, to design a systematic approach of building different modules of the robot. In this portion, we will use mathematical theories to model our system. This modeling we'll be done using a processing programming language like MATLAB. Plots and charts will be collected and saved for the final report. After the model is simulated and perfected, we will start the development process of each module. From the ground up, development on the main module will involve coding in python using a combination of algorithms from the OpenCV library as well as hardware integration using other functions found on the web.

6.1.3 Implementation

After the development is done, we will have to think about how we will implement the design using the hardware that is available to us. We will have to deploy all our codes to the computer system(s) that we will be using for different modules. Our understanding is that we will have three modules that need programming. The main computer system will use Python programming language, and the other two will be in C/C++ to process information. The other important implementation is the hardware portion of the robot. We will have the carrier board on the robot and make sure proper connections are made between different modules.

6.1.4 Prototype and Test:

At this point, all the modules are designed and implemented on the robot. Our goal is to set up an environment that is familiar to the design environment and can be used to test our robot. We will develop a testing criteria document to make sure that our robot performs as it is designed to do so.

6.2 Estimated Budget Costs

TABLE 6- PROJECT COST BREAKDOWN

Component	Quantity	Cost (ea)	Total Cost
Raspberry Pi 3 Computer Board	1	$39.95	$39.95
BQ21040 BMS Integrated Circuit	5	$1.34	$6.70
MCU: ATMEGA328P	2	$2.34	$4.68
Buck Converter (3.3 volt)	5	$0.58	$2.90
Buck Converter (5 volt)	2	$5.00	$10.00
Fixed 5V/2A Linear Voltage Regulator	2	$2.25	$4.50
3.7/4.2 2500mah Lithium Polymer Batteries	2	$7.99	$15.98
PCB layout charge	3	$15.00	$45.00
RC Sumo Jump Vehicle	1	$29.99	$29.99
Raspberry Pi accessory kit	1	$20.00	$20.00
Passives	n/a	n/a	$25.00
Wireless Keyboard/Mouse	1	$30.00	$30.00
HD Monitor	1	$80.00	$80.00
460mW/405nm laser	1	$70.00	%70.00
15mW/50mW laser	2	$20.00	$40.00
Total Cost	--	--	$355.40

6.3 Conclusion

There is currently a widespread need for a device that is capable of handling potentially violent or lethal situations in the blink of an eye, all the while with pinpoint accuracy. This need can be satisfied by the Stinger Autonomous Vehicle. With the superior steering capabilities of a two-wheeled vehicle combined with high-speed image processing and target detection, the Stinger is fast enough to react in an instant when exposed to a potential threat. This agile device is backed by a 500mW laser capable of vaporizing its target. If all of this sounds menacing, there is a great reason for that; the Stinger is not to be trifled with. Our team has collaborated in conceptualizing, designing, and prototyping this machine of war so that the groundwork for future improvements may be laid. The small form factor of the Stinger is designed to be scalable to a more practical and terrifying beast that will dominate the battlefield. Because of the limited budget that our team had to work to obey, our design was constrained to cheaper off-the-shelf parts that have somewhat inferior performance capabilities to those that would be utilized on military funded projects.

7 Appendices

This final section consists of the appendix, which is composed of the references the design team used throughout their research, additional figures that were not included inside the report, and datasheets.

7.1 Additional Figures

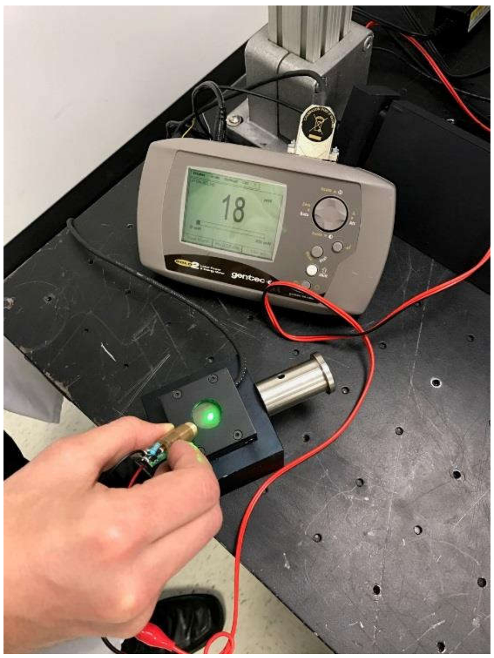

FIGURE 37- INITIAL TESTING OF LASER POWER OUTPUT

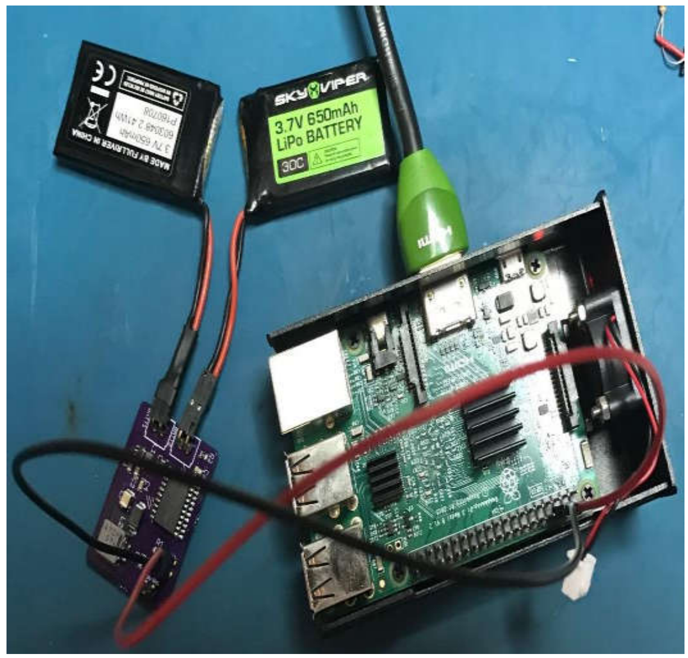

FIGURE 38-RUNNING THE RASPBERRY PI OFF OF THE TEAM DESIGNED PCB 5V BUCK CONVERTER

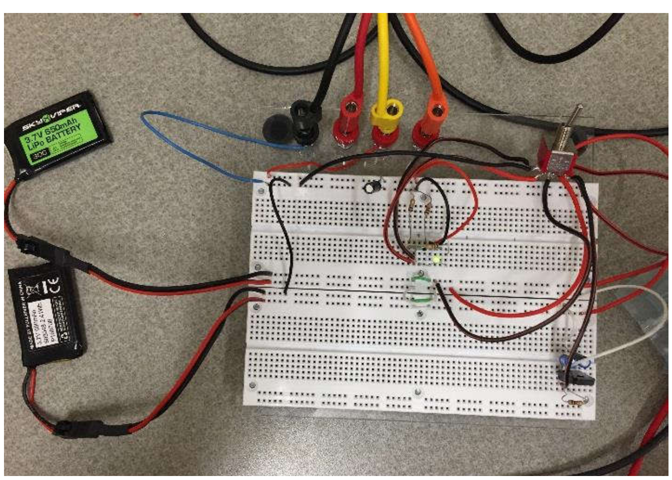

FIGURE 39- INITIAL TESTING OF THE BMS SYSTEM

7.2 References

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7.3 Datasheets

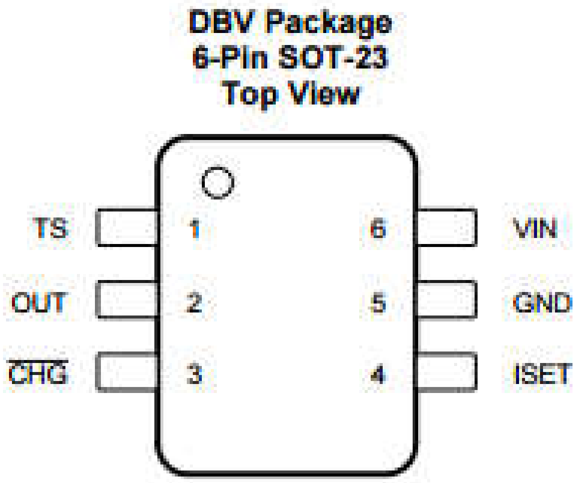

FIGURE 42-BQ21040 PINOUT

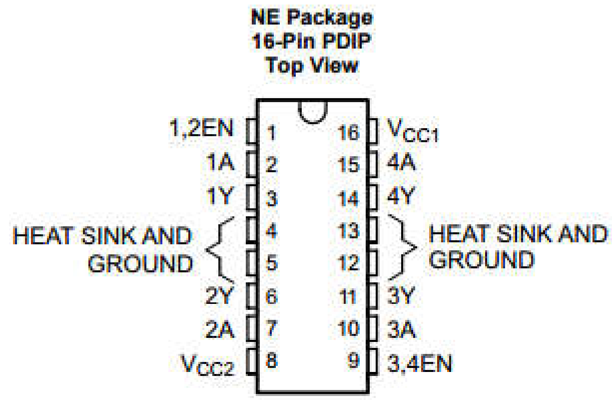

FIGURE 41-L293D PIN LAYOUT

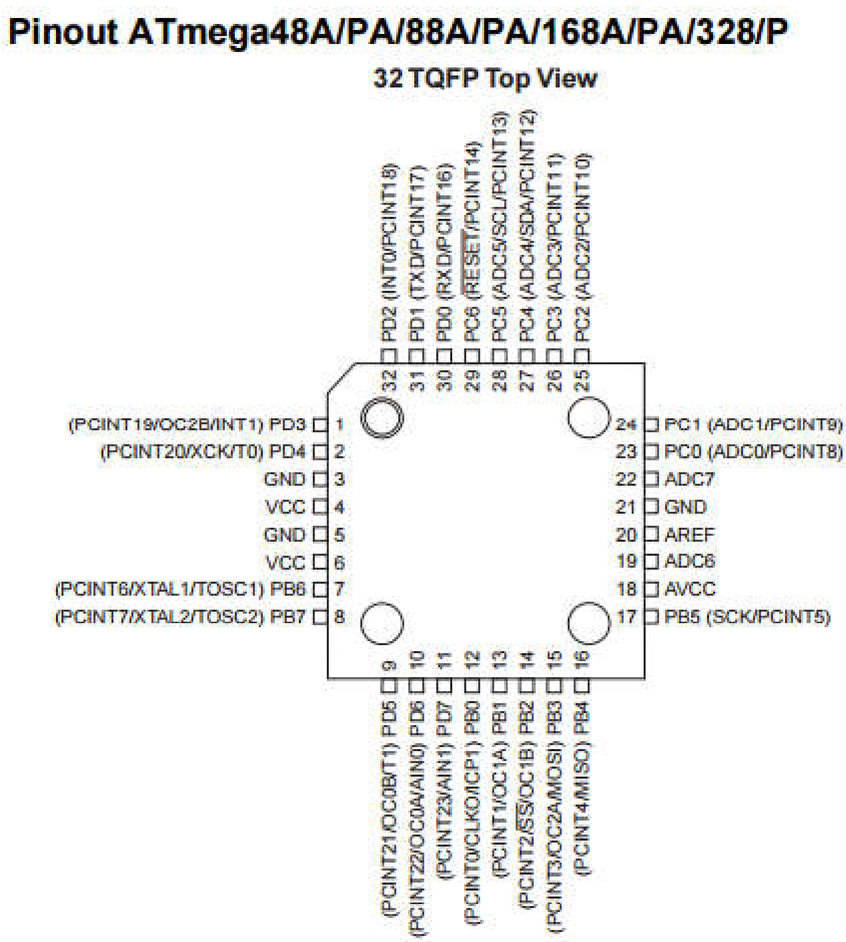

FIGURE 40-ATMEGA328P PIN LAYOUT