# Autonomous Pet Entertainment System

# (A.P.E.S.)


College of Optics and Photonics

College of Electrical Engineering and Computer Science

University of Central Florida

Dr. Lei Wei

Group 8

| | |
|---|---|
| Naim El-Nil | Photonics Engineer |
| Nathan Anthony | Electrical Engineer |
| Ricardo Serrano | Photonics Engineer |
| Cameron Alexander | Computer Engineer |

# Table of Contents

# List of Figures

# List of Tables

# 1 Executive Summary

Cats and humans form a symbiotic relationship that has its roots in prehistoric pest removal. Although now we view them more as companions than farm animals, cats are still highly specialized hunting machines, and this informs the way we entertain and interact them. Any small quick movement around a feline is bound to elicit a response.

During these trying times, many individuals are stuck working and studying from home, and many of us have furry loved ones to keep us company. However, as anyone with pets, children, or a spouse will tell you, they require attention and can be a detriment to productivity if not appeased. However, appeasing those you care for is time not spent on productive labor, what is an engineer to do? As seen in Figure 1 time spent sipping coffee with your cat is time not spent working.

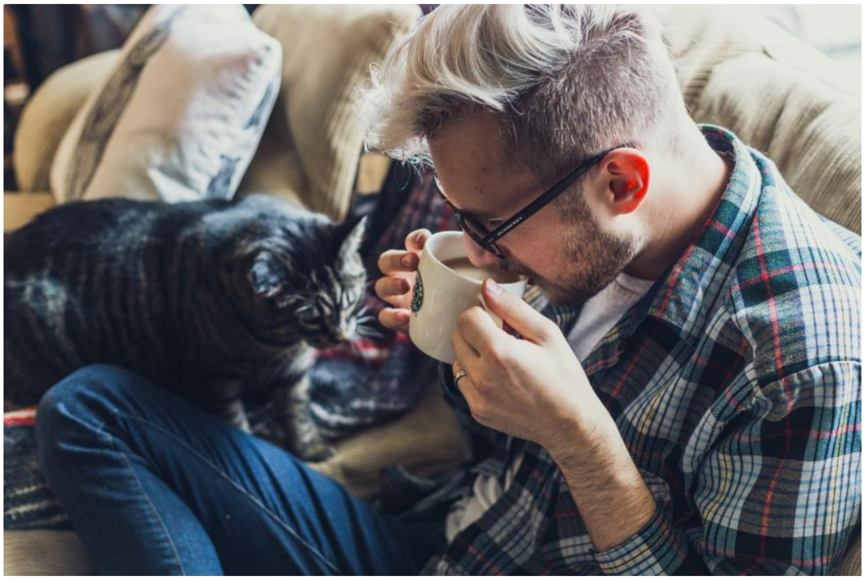

*Figure 1: Man with cat*

With greater demands of productivity automation has become an ever-increasing aspect of our lives. And while self-driving cars are not quite here yet, automating our lights and vacuum cleaners is something many of us are already used to. With an increasing population of people who spend the majority of their work day at home finding ways to automate task can lead to greater productivity. The project we propose in this document is meant to decrease time of the user spent entertaining their pets while also monitoring their pet autonomously.

The Autonomous Pet Entertainment System will allow for users to monitor and entertain their pets without having to get up and do it themselves and will hopefully reduce the number of knocked over cups and stepped on keyboards.
To accomplish this APES will use computer vision in the detection of the cat and optical detection to navigate its environment.

The APES will allow for users to entertain their pets remotely without fear of the system harming the pet or their property. And like the Roomba featured in Figure 2, it will detect walls and edges using optical sensors to avoid colliding into objects. It will also report if it has been knocked over and its location back to the user, allowing users to focus on other task without distraction.


*Figure 2: iRobot's Roomba, automated vacuum capable of self-navigation*

# 2 Project Description

The APES as the name implies is an autonomous pet entertainment system meant to provide the user a way to monitor and distract their pet without much input from the user. The system is meant to entertain pets and the user using an optical display in two modes. In the first mode the optical display is to play keep away with the user's pet, or the user if they are into that sort of thing, by tracking their movement and adjusting the position of the show laser accordingly. When engaging in the second mode of the optical display the APES will perform a light show using the show laser with modulating displays that make use of a motor-powered telescoping lens to increase the radius of laser display and diffraction grading sheet, also powered by motor, to create elaborate patterns by the display. The system is to be as the name implies is to be autonomous in its functioning of the show laser, to achieve this the system will incorporate a camera system to feed information to a microprocessor using computer vision. It will then use this information to determine the area in which to move the laser. The second primary function of the system is its ability to navigate its environment. For this we will incorporate wheels onto the bottom of the system to facilitate motion. The system will use a laser range finder and light emitting diodes to assist in the detection of obstacles that lie within its path and navigate around them. It will be capable of tight rotations and use this to navigate around corners and away from walls and furniture without the need for input by the user. The toy will cycle between two modes of function, show mode and navigation, fluidly.

Upon startup the user will determine whether the toy should seek to play with their pet or run a light show. If the toy is directed to play it will attempt to locate the pet using the vision on the webcam. If the pet is found it will try to entice it with the laser while keeping the laser a certain distance from the subject. If the pet is not found it will enter into navigation mode and relocate to another area, after a certain distance traveled it will re-enter scanning mode and attempt to search for the cat. It will continue this until it finds something to play with. In lightshow mode the system will navigate the area while displaying various different patterns on the surfaces of the room. To guarantee safety the system will use a low power laser less than 5mw while having a gyroscopic sensor to determine to if it’s oriented correctly, if not it will shut itself down. To guarantee portability the toy will be roughly the size of your standard automated vacuum, made from lightweight material, a combination of wood and aluminum, and completely battery powered.
While not crucial to the operation to of the APES, some features we wish to include as stretch goals to increase the usability of the system. This includes remote control, allowing the using the power the device and determine the mode of operation from a distance. Auto-recognition mode in which the device determines its mode based on whether it spots a human or a pet, this would function by having differing recognition algorithms trained to both human outlines and pet outlines.

Wireless feedback reporting that will allow the device to send notification to the device of the user's choosing to alert the user of the status of the device's operations, especially in the case that the device was knocked while outside the user's view. Included with the feedback reporting would be the ability for the device to be recalled to its starting location and navigate back to the user using a remote or cell phone/computer. And varying laser display colors that can be personalized based on the personal recognition of the camera. We hope to include one or more of these features despite not being central to the devices function.

In this section, we will outline:

- The motivation for choosing and building a pet toy, and how the members of the team influenced the decision.
- The primary goals for the pet toy which will be given more detail by its objectives. Possible testing scenarios will be included to observe if the APES meets its design criteria.
- The list of specifications for the APES with detailed reasoning for each spec to provide understanding on how it aids in achieve objectives. May include comparisons of the specs to other devices.
- A House of Quality diagram that shows correlations between engineering requirements against marketing requirements. This is to provide insight for our design.

~~1.~~

## 2.1 Project Motivation and Goals

During the year of 2020, the world was struck by the worst pandemic in over a century causing a massive shift in the lives of almost everyone on the planet. With so many people working from home and spending time with their pets we sought to create something fun that people could use to connect with their pets and loved one while also incorporating knowledge from the field of engineering to create something novel. The idea of pet toy came from the general idea of combining photonics, electrical and computer engineering into something lighthearted.

Many people in the country own pets and they can be a handful if not properly cared for. One aspect pet care is of course making sure that your pet has the time and attention it needs to feel fulfilled. While the APES can be used for multiple different kinds of pets and even children, the primary reference point for our design was in keeping the attention of our favorite felines. Cats even more so than dogs are ruthless when it comes time to give them attention, although as any dog owner would tell you, whether they like to be the center of attention when compared to dogs is debatable and can be persistent when they feel it is their turn to have the attention of their owner. Social play, as it is called by experts, is vital to the healthy growth of a cat and allowing them to not only mature in body but also mentally by teaching them boundaries and predatory behaviors, according to Meredith West of the Department of Psychology at Cornell, in her paper *Social Play in the Domestic Cat*.[17] And when not given enough attention cats can engage in common destructive behavior, such as knocking things off shelves and tables, scratching at furniture, chewing on plants, excessive grooming which may lead to excessive hair loss and litter, and the consumption of not food items, commonly called Pica according to experts [18] and a nightmare to any engineering student with small shiny components laying around. Not only is attention needed for physical health but cats who are left alone for too long can suffer from various neurological effects also, this includes a lack of appetite, unusual sleeping patterns, lack of interest, anxious and aggressive behavior. These signs point to depression in the cat that is often a sign they may feel alienated and uncared for.

However, with the onset of the corona pandemic millions of Americans are forced to work from home, and while accustomed to their owners work hours, cats may see the increased presence of their owners as an invitation to demand more attention and might respond negatively when their owner is busy working from home. Despite the removal of commute times to jobs and office dress codes, professionals who work from home are put under more pressure than in the office. In many cases they are responsible for their own office supplies needed to complete the task required of them, internet and electricity is also something the professional may be asked to provide for themselves too. And if that professional is being extra cautious, they may be quarantining in place and rely upon delivery to acquire vital resources such as food and medicine. All this can add up to the worker needing to accomplish more at work to guarantee profits and their salary can cover their unexpectedly increased cost of living. This can lead to a stressful environment for the owner and the pet alike. This is the problem the APES is designed to solve. Providing an easy-to-use entertainment device that a user can turn on and use to engage their pet while not requiring their personal attention. This allows the pet to get the play time it needs while allowing the user to focus on more productive task. Efficiency, the life blood of all engineering.

Since this project consists of three different disciplines (photonics, electrical, computer), we needed to add enough features so each group member can contribute equal effort to the research, testing and assembly of the APES. A laser pet toy was considered and picked by our group members because it can incorporate these disciplines seamlessly also while being a simple and not very difficult project.

For the photonics aspect, we have two members under this discipline so most of the core features come from this. The components that fall under photonics, which will be given more detail in the specification section, are laser diodes, light sensors

(LEDs and photodiodes), lenses and diffraction gratings. While each of the components may have simple functions, complexities of the project arise with their combinations such as with the show laser (laser for the cats to see) and the IR rangefinder that utilizes triangulation.

For the electrical aspect, we have one member who is responsible for the internal wiring and logic of the microcontroller, power supply for the several motors, servos and other devices, and gyroscope installation. This amount of responsibility is thoroughly enough for one member, but he will be involved in different parts of design such as wheel selection.

For the computer aspect, computer vision is complete task with a large enough amount of responsibility for one member along with necessary software design and coding needed for the various components. Computer vision that utilizes a camera is mainly software that will need to be built on a raspberry pi.

The APES is a laser pet toy where most of its design decisions come from the requisite to be unique and considerably different from the rest of laser pet toys on the market. This is a central tenet of motivation to our design and many specifications were made in mind of it. In order to accomplish this, we gave the APES characteristics that combine and alter the characteristics of all the other various laser pet toys on the market. The primary goals of our APES is as follows:

- Utilize a highly visible laser that can distract a pet with its erratic and spontaneous movement.
- The show laser must be capable of changing its size (magnification) and its shape.
- Navigate its surroundings by avoiding any near objects which involves distance measuring.
- Use computer vision to identify the cat/or object in front of the device.
- Detect if the device has been turned over.
- Minimize all possible harm and make safety a priority.
- Be completely autonomous when active.

To achieve our first goal, we will mount our laser on the very top of the device where it will have servos attached to it to give it a degree of freedom to rotate vertically and horizontally. The laser beam is intended to shine at a place where the cat can easily reach it which would be the floor and low portions of a wall. Its movement algorithm will be designed to not follow a generic pattern and will be mostly sporadic. To achieve sporadic movement, several different movement algorithms will be constructed, and a random number generator will switch between them based on a time limit.

To achieve the second goal, a telescopic lens system will be implemented where a motor will vary one of the lenses' position which will change the size of the beam. Another motor will be used to control a wheel holding several diffraction patterns so when the beam passes through it, the general shape of the beam will change. These elements will move with the laser as it moves.

To achieve the third goal, various IR sensors which consist of an IR LED and photodiodes will be placed around the perimeter of the device so if an object gets to close to it, the device will move in the opposite direction. For propulsion, it will need motors connected to each wheel and there must be a wheel to help rotate the device easily. For navigation, IR lasers and photodetectors will be used in a laser rangefinder where object distance will help the device in navigation.

For the fourth goal, the webcam will utilize computer vision to identify an object/or cat directly in front it and the laser rangefinder will be able to communicate that object's distance. This in turn helps the algorithm determine what its best course of action is in response to the object's specific distance. An object can be used in place of a cat since testing a real-life cat may have some complications associated with it such as the cat's behavior, availability, etc. Our project is designed in thought of being able to identify a real cat.

For the fifth goal, a gyroscope will be installed to communicate to the device's CPU if it has been knocked over or tumbled. This objective it to aid in our safety goal to minimize harm. When the device has been knocked over, the device will need to shut down all of its optical elements including the show laser, IR rangefinder, and IR sensors. This is to avoid the beams being pointed at objects it should not be pointed such as a person's eye. The safety goal is additionally satisfied by the show laser's random movement where if the beam was stationary for too long, it may be capable of serious damage to biological tissues or even non-biological material such as TVs.

For our last goal, autonomy includes no user input besides turning it on, and if it was knocked over then fixing it to its original position. All of the algorithms of the device are made in mind of keeping the device completely separate from any additional help which includes its laser movement, navigation, and propulsion. Within our algorithms, there are given scenarios for our device and what the device does based on those scenarios is what will need to be tested for intended functionality. For instance, if the APES is active and we take a box and place it on the side of it, the device should be able to automatically detect it, reference its algorithm for the most relevant scenario to this case, and should follow the algorithm accordingly (move to the opposite side). The APES will need to be able to follow all the above goals and objectives completely by itself.

The APES is designed to be an automated device that can function with very little user input. It should be able to navigate its environment while detecting objects and avoiding collision with surfaces in the area. To accomplish this the system will make use of a laser range finder and light emitting diodes to act as optical “bumpers” that alert the toy when it is getting too close to a surface and redirects its path. It should be able to tell how long it has been in transit and how far it has moved. It should be able to identify the pet amongst other objects of similar size and differentiate between the pet and the environment around them. It should be able to operate its mounted laser with 2-dimensional freedom and be able to swap the diffraction gradient and telescopic level quickly to create a variety of visual effects.

Engagement with the user's pet should be done autonomously without need of user input except during the power on sequence. It should be able to swap modes between navigation and laser display quickly enough as to having the appearance of one continuous action. We want the system to be approachable by the cat so that it wishes to engage with it while not attracting the cat enough to ignore the display and attack the machine itself. In the event the cat does attack the toy it should be able to withstand any strikes from the cat without sustaining any damage that would require repair or cause the toy to stop functioning after it is powered on. The toy should cease functioning if knocked over to prevent it from taking any more damage and should be able to terminate its programs gracefully such that simply turning it back on will allow it to resume normal functionality.
Some stretch goals of the project include as mentioned in the description, wireless communication that will allow users to activate the system wireless over Wi-Fi, and then to also set the mode of operation from a distance also. This could be achieved using a Wi-Fi signal and a personal computer or cell phone. Alternating laser emitters could be used to personalize the display for each pet along with an increase in the accuracy of the detection algorithm to improve upon detection. This would allow the system to determine which pet or person it is looking at and adjust the laser used for the display accordingly.

## 2.2 Objectives

To accomplish our above-mentioned goals, we will have 4 primary objectives.

1. Detection of environment through the use of laser range finder and LED lights
2. Detection of the pet while still or in motion via the use of webcam and computer vision software
3. Communication between sensors and microcontrollers to facilitate motion
4. Alternating laser display using diffraction grating and a telescoping lens capable of changing the shape and size of the display

The APES will use laser range finders to detect objects in the environment when autonomously navigating any environment it is placed in. Our in-house developed rangefinder utilizes an infrared laser beam to detect the distance of the nearest object in the direction of movement of the toy. The system will also feature a pair of photodiode devices to detect said beam and report the distance back to microcontroller as to prevent the system from colliding with other objects. By using trigonometry, the APES can check where it's position in relation to the rest of the room and will use the rangefinder to measure the distance of any object in-front of it. Pairs of infrared LEDs and photodiodes are attached to the side of the APES system to aid in navigation as well. These device pairs will act as an optical bumper system to assure that our system is aware if any object or person gets within range of it from the side or behind. This gives the system 360 degrees of special awareness and should keep the object from any unexpected collisions with objects not seen by the camera or rangefinder.

APES will use a webcam to identify the user's pets and track their motion using computer vision. The webcam will be driven by a microprocessor running the openCV software to run detection algorithms on the room around the toy. The camera will take in a video feed of the room and send individual frames of video data back to the microprocessor via of the use of the VideoCapture() function present in openCV and send them to the microprocessor to be analyzed. The microprocessor will use the frames to determine if the cat is present in the room by running the software's CascadeClassifier class and method. The microprocessor will then capture the positional data of the cat in relation to the toy. The camera will communicate with a microprocessor to determine where to point the laser display in relation to the motion of the user's pet. By determining the view distance of the camera in relation to the system we can estimate the cat's position and send that data back to the system to determine which direction the laser should be pointed in. While this mode is active the microprocessor will communicate with the microcontroller to remain stationary, movement cause disruption in the detection algorithm and gives the appearance of motion where there is none. In the event the detection algorithm does not detect anything in frame to be motion tracked, the microprocessor will communicate with the controller to enter into navigation mode for relocation. The camera will then cease function allowing for the preservation of power in the system. When the navigation is over the camera will be restarted and scanning algorithm will begin again.

As mentioned before the microcontroller will read input data provided by the optical sensors to determine the position of the system in relation to its environment and move accordingly. This will drive the motion of the system by having these sensors report back any obstructions in the path of the system. The microcontroller will then communicate with wheels motors to begin motion by sending a pulse with modulation signal out of the controller and to the motor. By sending a PWM signal with a certain duty cycle, time in which the signal is on, we will be able to control the speed in which the system accelerates and decelerates. By combining this with the communication with the laser range finder, the system can determine how far away an object is and begin to stop by using a formula that takes in distance and converts it to the appropriate PWM signal to send the motor. The system if suddenly obstructed can also be told to move in reverse before doing any more movement actions until there is enough distance for it to resume its normal movement routine. The system will be able to rotate in place just like a Roomba and should navigate the room in a similar two-dimensional fashion. Since the toy is meant to only seek out pets the more robotic two-dimensional motion allows us to save processing power.  Navigation will take place over a certain distance; in the event the distance of travel is lost it will also be on a timer before reverting back to scanning mode. During navigation the camera will be off, and the primary function of the raspberry pi will be to do any calculations, such brake speed and acceleration, that might slow down the ATMega. Further testing is needed to determine the optimal division of work between the two microcontrollers, but the goal is to maximize the response times of the system while in motion and minimize the time it takes to begin scanning once navigation has been paused.

The primary feature of the APES is its laser display. The display will have two modes of function, a mode in which the laser is a single point and combined with the webcam acts as a toy for the cat to play with. In this mode laser will not utilize any diffraction grating or telescoping and will simply be the laser pointed in the same direction of the camera. The laser will be servo mounted and capable of motion along both the x and y axis. When the camera sends the raspberry pi the video information it has detected, the pi will use this positional data to calculate the location of the cat in respect to the point of view of the laser. It will then be able to output to the laser servos the angle at which the laser should be adjusted as to be in a different location than the cat, with the ultimate goal being a smooth transition of position in which the laser does not touch the subject while moving to a new position and the subject is unable to reach the laser in for any extended period of time, goal is less than a second.

When not in play mode the laser will have a different set of operations. It will mimic a more random pattern of movement, while the raspberry pi will be in charge of running the motors connected to the wheel gradient that will determine the pattern of the laser display during the lights show and the telescoping lens motor which will determine the radius of the display. This mode should be compatible with the navigation mode, allowing for the system to both move and perform its random light show at the same time.

## 2.3 Requirements Specifications

These are the intended specifications for our device and are subject to change during the assembly and testing phase. Some specifications are more theory-based and will most likely not change such as wavelengths, but specs that are more likely to change are sizes and ranges. In this section we will detail the reasoning for the specifications meaning why it is important to have these requirements.

In order to fulfill the show laser's spontaneous movement, it is important to give the show laser a degree of freedom to rotate and move its beam accordingly. 180 degrees horizontally means the laser beam will be able to move to any direction surrounding the device (full circle), and 75 degrees vertically gives the beam variable movement towards the floor. We want to design the laser beam to mainly be pointing down on to the floor, and the highest point the beam should be able to point is parallel to the floor. This is to avoid any potential harm of hurting a human's eye where the beam would be pointing upwards. The lowest point vertically that the beam should be able to point is roughly a few feet from the device. This is a physical constraint since the beam cannot point directly down since that is where it is connected to. The exact vertical degrees of rotation are only a rough estimate and is subject to change during assembly.

For the show laser, its wavelength needs to be in the visible range as to distract the cat and do the show projection. Its wavelength is 532 nm which is in the green part of the visible spectrum and makes it highly visible according to Fig. ##. This figure shows the optical spectrum and relates wavelength to relative eye sensitivity. The visibility of a laser depends on its signal to noise ratio (SNR) which is the power of the laser to the noise from the background non-laser illumination. The higher SNR means the laser is more easily seen by us and the cat, and the curve of the graph shows that the wavelength with peak sensitivity to the eye is 550 nm. Our laser light at 532 nm puts it really close to the wavelength with peak sensitivity. This is ideal for us since our show laser must be highly visible with its projections. Additionally, the green laser makes it unique from other devices since most of the laser pet toys use a red laser and helps us achieve our goal of making a distinct pet toy.

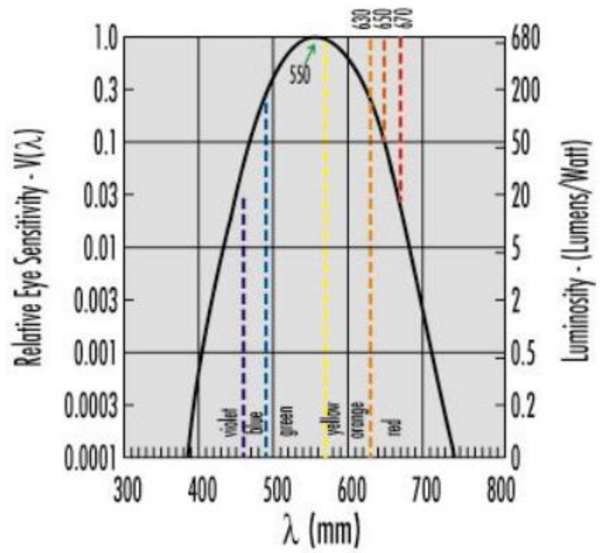


*Figure 3: Relative Sensitivity to the Eye*

The wavelength of the rangefinder laser was picked to be in the infrared region of the spectrum since it is invisible to the unaided eye. It needs to be invisible since this laser's purpose is for distance measuring and has no necessity for being seen. There are accompanying photodetectors that will sense the IR laser light and aid it in its objective. 1064 nm is relatively safe and common laser wavelength that is commonly used in various applications such as tracking, communications, and scanning. This laser poses similar risk to the show laser in that it is capable of damaging biological tissue but includes more risk since it is invisible. Even though it is relatively low to the floor, the IR lasers may still hurt the cat if the cat is in its line of sight. There are multiple possibilities that the APES will consider such as placement, output power, activation time, etc. that is detailed in further sections.

The laser rangefinder detection range is a rough estimate and is one of the specifications subject to change under testing. The APES should be able to detect objects within its field of view that are relatively close and relevant. This is to help the algorithm responsible for navigation be able to choose the best course of action to move the APES in relation to object's distance in front of it. Three feet minimum in front of the rangefinder is to avoid saturation on the photodetectors and near-field optics that may hinder the necessary calculations for distance measuring. Thirty feet maximum is an estimation of the minimum amount of IR light the detectors can pick up at that distance with a reasonable SNR. The maximum distance is most likely to change based on this parameter.

Maximum laser power is the greatest amount of optical power that our lasers can be at to be considered safe under laser safety standards. While this is the maximum amount, it may not be our point of operation based on other conditions detailed at later sections. Most lasers used in other pet toys are not nearly this powerful, and the APES may follow suite.

We want the spot size magnification of the show laser's beam to be able to be detected as a separate size of the beam at variable magnifications. For instance, the 1x beam size is the original beam with no magnification with its own diameter of 5 mm (for example). The APES should be able to magnify this beam size by 2x so it is 10 mm. However, if the 2x beam looks too similar and not distinct from the 1x beam, then we would make the magnification be 2.5x at 12.5 mm. This 2.5x magnification would be one the variable magnifications the APES is capable of along with all the other distinct beam sizes like 4x and 5x. The maximum magnification we are aiming for is 5x with at least three variable sizes between 1x and 5x (including). Beam magnification is a feature of the APES unique to it that makes it different from other pet toys which fulfills our goal.

The specifications of speed, battery life, weight, cost and dimensions are specs to accommodate the main goals of the APES and are not high priority to keep static. These specs are made with estimation (e.g. not necessary to design) and are most likely to change based on convenience and complexity. The speed of the APES at 1.5 miles per hour should be fast enough to navigate its surroundings in a reasonable amount of time. Speed is tied to our motors and RPM of the wheels and will be tested accordingly to know if the speed criterion can be met. Again, speed and time of navigation is not a major part of our design, but it will be considered in our navigation algorithm.

Number of batteries and minimum battery life are specs that will most likely remain static as it deals with power supply and division to all of our motors, servos, controller units, and IR sensors. The laser diodes come with their own batteries and will not rely on the power supply specs listed here. The minimum battery life is an estimation of the power loss along the components combined. This is a spec subject to testing and may be altered under circumstances.

The cost to design the project will be as low as possible and is specification that is considered when designing all components of the APES. 500-600 dollars maximum should be more than enough to get all the necessary parts since the parts are not very complex or obscure. For instance, the laser diodes cost around 20 dollars each since these are common electronics that are mass produced for consumer availability. Most of our components purchased will be the most common type rather than an expensive, highly refined type since the APES is only trying to achieve simple goals and objectives.

Weight and size of the APES are most subject to change as they are very likely to change as we start assembling it. For weight, our construction will be using light objects since the APES needs to navigate reasonable distances so 1.5 pounds is a reasonable estimate. The radius and height of the device needs to be relatively small for maneuverability, stableness, and weight. The height of the object needs to as large as possible since at the apex the show laser will be placed at and be pointing towards the floor. The height is to give the show laser a dynamic range to direct its beam around. The radius of the device will be considered with sensor placement and their FOV. We will need enough sensors to cover the perimeter, but not overlap.

*Table 1: Engineering Specifications*

| **Engineering Specifications** | | |
|---|---|---|
| **Specification** | Value | Unit |
| **Vertical Laser/Camera Movement** | 75 | Degrees |
| **Horizontal Laser/Camera Movement** | 180 | Degrees |
| **Laser Wavelength (Show Laser)** | 532 | nm |
| **Laser Wavelength (Laser Rangefinder)** | 1064 | nm |
| **Laser Rangefinder Detection Range** | 3 - 30 | ft |
| **Laser Power (max)** | 5 | mW |
| **Spot Size Magnification** | 5 | x |
| **Speed** | 1.5 | fps |
| **Battery Requirement** | 4 | AA |
| **Battery life (min)** | 5 | hrs |
| **Obstacle Distance (min)** | 8 | in |
| **Weight** | 5 | lbs |
| **Cost** | 600 | $ |
| **Radius** | 8 | in |
| **Height** | 16 | in |

## 2.4 House of Quality

The design tool shown in Figure 4 is the House of Quality used in the development of our product. It allowed for the creation, visualization, and management of marketing requirements, engineering requirements, and the relationships between the two.

Marketing requirements are the specifications that a consumer would be interested in when considering the purchase of a product. The first requirement a consumer would consider would be the cost. When listed under marketing requirements, the cost refers to the price that the end user would pay. The lower this cost, the more likely a consumer is to purchase the product. Safety is another requirement that is of great importance. If there is the potential for the product to harm the consumer's beloved pet, then it is very unlikely that the product will be purchased thus safety must be maximized. The battery life should also be maximized since the product is to operate autonomously. The product will suffer if it is not intuitive to set up, therefore the ease of use is to be as high as possible. The durability of the product is another key requirement due to the autonomous nature of operation and the intended use. The product is likely to be attacked eventually in some capacity and should be able to retain functionality.

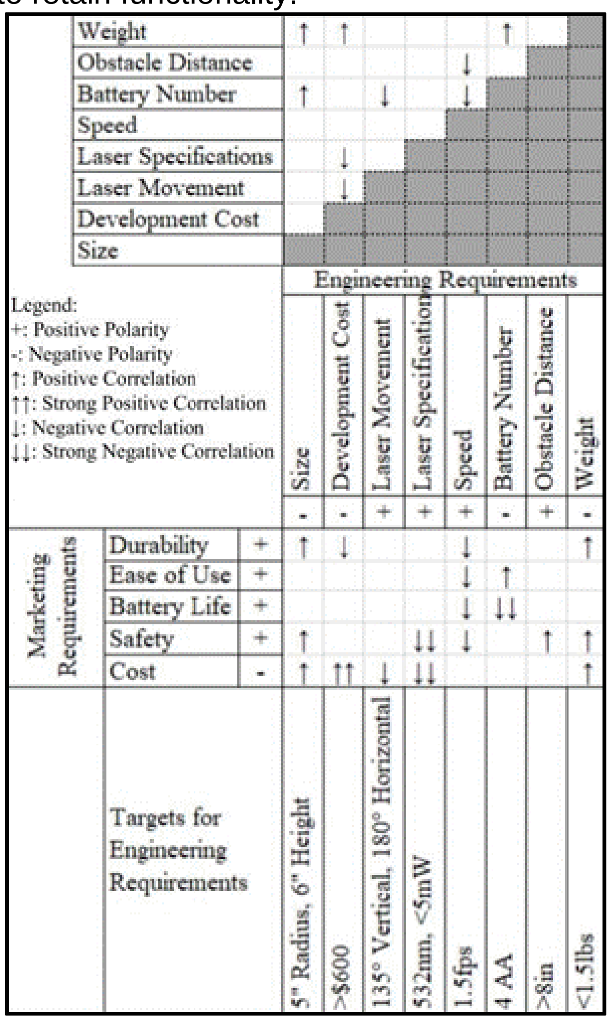


*Figure 4: House of Quality*

Engineering requirements are the specifications considered by the designer of a product during the development stages. Specifications such as the size and weight are factors to be minimized for many of the same reasons; The smaller the device the easier it is to maneuver autonomously however it does negatively impact the development cost as smaller components become more expensive when precision is needed. The weight will affect the durability, speed, and battery life directly. A lighter device will require a thinner, more easily damaged construction. A heavier device will put more stress on the motors to move it, decreasing battery life and top speed. The laser specifications impact the safety of the product in that the lower power laser we use, the safer it will be. The laser movement range dictates many design elements for the outer shell of the device, requiring clear or open areas of the shell which could potentially create durability issues. The obstacle distance refers to how close the device will allow itself to become relative to environmental obstacles. This specification coupled with the speed will ensure the safety of objects in the area of the device as well as prevent unnecessary damage caused by collisions. The development cost has the most implications for other specifications. Everything suffers when we decide to buy cheap components over more reliable, expensive ones. However, we must work on a reasonable budget or the price for the consumer will need to be very high to offset the cost of development.

# 3 Research related to Project Definition and Part Selection

This chapter includes discussions of the research that was performed in the development of the APES. The research stage of development is one of the most crucial; An overview of products available on the current market and how they pertain to the design or development of the APES will reveal if the product or idea has already been developed and marketed as well as identifying key technologies or practices used in today's products. A discussion of technologies reviews many of the key technologies identified as they pertain to the feasibility of the APES.

Once the feasibility and market availability of the idea has been justified, the selection of components becomes necessary to create designs and schematics to further develop the system.

## 3.1 Existing Product Investigation

As with many products found on today's market, the APES is a combination of many existing technologies which complement each other to produce a smarter system and overall improved operation. This section will cover many products currently available that have similar operation or intended purposes as the APES. This does not show all available products, but a small number selected to show the common design aspects within each category of product.

### 3.1.1 Autonomous Vehicles

This section covers a selection of products that showcase the current state of the market in terms of autonomous navigation for cat toys and other autonomous devices.

**Biilaflor Peek-A-Boo**
This product uses a very simple form of autonomous navigation in that it only uses touch sensors. The toy will move until it is touched, or it runs into an obstacle in which case it will move in the opposite direction. This product also uses the exact propulsion scheme as the APES: two independent rear wheels with a free-turning castor at the front.

The primary entertainment method is a small interchangeable toy mounted to the inside of the chassis that will randomly appear out of holes around the body of the toy.

**DELOMO Automatic Rolling Ball**
The same form of autonomous navigation used in the previous product is employed here but at much higher speed. The ball rolls itself until it is touched or

encounters an obstacle and moves in a different direction. The manner of propulsion involves rotating the entire toy as a wheel to entice cats to attack it. This movement scheme limits the toy's ability to traverse thick carpet.

**iRobot Roomba**

The Roomba robot vacuum shown in Figure 5 represents a more complex way to navigate autonomously about a space. It uses a combination of strategically placed infrared and touch sensors to navigate around objects, avoid ledges, and remain within predetermined areas of operation. Apart from remaining within predetermined areas, the APES will navigate in a similar fashion via infrared sensors. The propulsion scheme also matches what will be employed on the APES. [1]

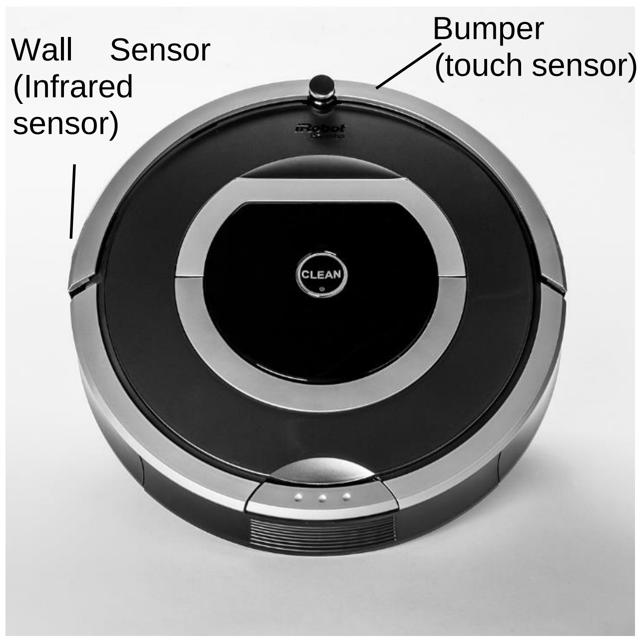


*Figure 5: The model year 2014 iRobot Roomba 782 Hoover Sensor Approximations*

Reprinted with modifications.
Original Photo by CEphoto, Uwe Aranas

# 3.1.2 Autonomous Laser Pointers

This section discusses various products that show current trends among autonomous laser pointer design such as that found in Figure 6.

**HIPIPET Automatic Cat Laser**

The HIPIPET cat laser is a stationary toy that has a rotating top half that emits a red laser. The toy moves the laser in short bursts of back-and-forth motion at random points all around the toy. After four minutes of continuous operation the toy will enter a standby mode which is disabled upon movement detection or a touch to the shell of the toy.

**DAMGOO Light Toy**
This toy is stationary with a laser pointing upward from the main body onto an adjustable mirror which redirects the beam out at a downward angle. The laser itself rotates in a circular motion with random direction changes. This toy is meant to be placed on a table or shelf above ground level so that it is less likely to be knocked over and so that the laser covers a larger area.


*Figure 6: Common Design of Automatic Laser Cat Toy*

Reprinted with permission from flckr

**EKOHOME Cat Toy P09**
Very similar to the DAMGOO, this toy is stationary with a laser pointing out from it in a set direction. This laser moves in an elliptical motion with random direction changes. This toy has the option of being mounted directly to the wall via screws, a suction cup, or placed on an elevated surface with the removable base. Simple motion detection is used to wake the device from the standby mode entered after five minutes of use.

## 3.1.3 Laser Displays

This section discusses products that utilize lasers and diffraction gratings for projected decoration purposes.

**LedMALL Motion Pattern Firefly**

This is an outdoor unit that is meant to project themed patterns onto a building. The system uses combinations of three different colored lasers and multiple diffraction gratings to create a regular, repeating pattern of shapes selected by the user based on the desired holiday or event.

**Chims Mini Laser Lights**

The Chims mini laser lights uses a similar system of three different colored lasers and multiple diffraction gratings in a handheld-sized unit. This is meant for indoor events and has the capability of sound activation. This does not use holiday themed shapes, instead creating patterns of symmetrical objects, spirals, and other shapes.

## 3.2 Relevant Technologies

This section will cover how many of the technologies that will be included in the APES function on a broad level.

## 3.2.1 Microcontrollers

Microcontrollers are small computers on single MOS (metal oxide semiconductor) chip, distinguishable from their microprocessor cousins which can have multiple computers and chips. Microcontrollers (MCUs) are the realization of Moore's Law applied to MOSFET transistors created circa 1960. Allowing hundreds of transistors on single MOS chip allowed for engineers to design computers that could fit on a single chip. Today microcontrollers are the basis of embedded systems and used to control the thousands of devices we use today with varying computational power. From car systems to refrigerators MCUs allow for electrical and mechanical systems to sense their environment and respond. For our project, a microcontroller will be used to interpret sensory data and then drive the motion of the system, determining where to go and how quickly. We will also use a microprocessor for the computer vision necessary to identify and track the user's pet.

Microprocessors and microcontrollers originate from the invention of the MOSFET, or metal-oxide-semiconductor field-effect-transistor, invented in 1959 by Mohamed M. Atalla and Dawon Kahng while working at Bell Labs. The next year Kahng would propose an integrated circuit chip made from these transistors which would become the grandfather of the modern-day integrated circuit. With circuits magnitudes smaller than those constructed by the discrete electrical components of the past, technological advances have made it so we can fit literally billions of transistors in an extremely small space allowing for computers to have millions of times the capacity and hundreds of times the speed of computers made prior to their widespread integration into our electronic society. This advancement is so significant that modern day electronics rarely if ever feature discrete transistors and have allowed us to integrate smaller electronics into almost every aspect of our lives.

The evolution of the MOSFET would be realized with the first microprocessor created in 1971 by Intel, called the Intel 4004, it was the first processor located entirely on a single MOS LSI chip. The first microcontroller would be developed by the same year Texas Instrument in the TMS 1000.The microcontroller was a huge leap forward from the microprocessor done in less than a years' time. While the microprocessor was revolutionary in being able to bring processing power inside a small chip, a microcontroller was an entirely different beast, it would allow engineers to have a full computer on a chip, not only a processor but memory, clock and i/o capabilities all stuffed on a single chip and would be the forefather to the modern SOC (system on chip) that we see today when we purchase a Raspberry Pi or Arduino online. In 1993 the introduction EEPROM memory or electrically erasable programmable read-only memory would further revolutionize micro controlling technology by allowing microcontrollers to be in-system programmable. Meaning now your processor would no longer need to be programmed using specialized hardware and could be placed in the system you wished to use it in and then programmed and reprogrammed to fit the needs of the system. It is this ability that allows our project to function at all. This ability to rapidly prototype and redevelop a program inside our system allows for senior design projects that can be completed using SOCs and processors in less than six months.

For our project we will be using an ATmega328 microcontroller to operate the navigation system in the APES. It was created by ARmel in the megaAVR family and is primarily used when a system is need of a low powered and low-cost microcontroller. It's of course most notably known for its use in the Arduino development environment. It features 23 general purpose I/O pins which allow it to act as hub for numerous components inside an embedded system. Internal and external interrupts allow for it to react in real time to the environment around it which is basis of the APES system. Our system is dependent upon punctual response to optical data while moving and the ATmega's external interrupts are what makes that possible. It's low voltage operation also allows us to divert more power to the more power consuming Raspberry Pi 3B, and the show lasers while still being confident the Atmega will be able to accomplish task. The major drawback however is that it is relatively slower than other processors and needs assistance when it comes to high level programs such as the openCV software we intend to run for this project.

Along with the Atmega the second microcontroller we will need is the Raspberry Pi 3B. Our project relies on high level computer vision technology that would just not be able to reach actualization with a simple processor like the ATmega328. The

Raspberry Pi was originally developed as a teaching tool for chidren in schools and developing countries. However, the popularity of it led to a massive expansion of its scope and capabilities. Developed by the Raspberry Pi Foundation in the UK the Raspberry Pi 3B uses a much more power Broadcom BCM2837 processor when compared to the ATmega328 processor. This massive leap in performance is necessary due to the nature of computer vision relying on running artificial intelligence algorithms and processing image data multiple times a second. Furthermore, while the ATmega has 32KB of memory the Pi features an entire GB, while this is a huge leap, the pi also requires an operating system to run while it processes the image data, so a large pool of memory is necessary for operation. The Pi also has a 40 GPIO allowing it to connect to other systems easily. In our case the Pi will need to connect to both the ATmega and drive the show laser at the same time.

### 3.2.2 LEDs

Light emitting diodes (LEDs) are a semiconductor electronic device that will generate light once enough electricity activates the system. LEDs are simply basic electronic diodes that take advantage of the property of spontaneous emission to produce visible photons of light. Diodes are created by combining two semiconductor metals in specific quantities. One of these metals contains more electrons than electron holes (simply, holes) which classifies the material as N-type. The other metal contains more holes than electrons and is classified as a P-type material. When a P-type and N-type material are combined, they form what is called a PN junction. The PN junction contains three primary sectors: The P-type side, the N-type side, and the depletion region. The depletion region is where most of the electrons and holes of the two materials combined and formed a region for nearly restricts all electron flow. However, the P-type side and the N-type sides contain barriers of energy that can allow electron flow through the depletion region once overcome. This energy barrier is referred to as the bandgap energy. In order for the electrons in electricity to flow through the PN junction, there must be enough electrons pumped on the P-side to overcome the bandgap energy. Pumping energy on the N-side will create a larger, inefficient bandgap energy that will electrically short the diode and destroy it which is known as reverse bias. Once the P-side is pumped with enough energy to overcome the band gap, electrons can undergo a process known as quantum tunneling and reach the N-side hence, electron flow. The device has begun the process of forward bias and will start to electrically short without a load in the circuitry. If the energy on the P-side drops below the required energy, the diode will shut off. If the energy on the P-side is continuously increased, the electron flow will increase exponentially until the diode shorts and begins to destroy itself.

When electrons tunnel through the depletion region of a semiconductor, the direction the electron travels is related to the quantum energy field geometry formed by the bandgap energies of the P-type and N-type sides. If the electron travels in a straight direction when tunneling, the electron has traveled through a direct bandgap. If the electron tunnels in any other direction, the electron has traveled through an indirect bandgap. Regardless of the type of bandgap, electrons spontaneously produce photons of light that are emitted once tunneling has occurred via the process of spontaneous emission. These photons are only able to escape the diode if direct bandgap tunneling occurs. Photons are absorbed by the material if indirect bandgap tunneling occurs. Diodes that are manufactured specifically to generate photons are known as LEDs.

The light produced by a LED is incoherent and is typically monochromatic with a broad range of photon energies and phases. Emitted photons are ejected in any direction originating from the PN-junction. This means that the efficiency of LEDs can be quite low. To combat this, LEDs are manufactured with different geometries and materials to aid in light escaping the diode.

### 3.2.3 Laser Diodes

The lasers found in our design will be generated by optoelectronic devices known as laser diodes (LD). LDs are semiconductor devices that work of the same principles of traditional lasers within a semiconductor package to produce coherent, monochromatic light. Lasers have 3 primary components that allow them to lase: A pump source, a gain medium, and an optical resonator. The laser pump source is any source that can provide energy to the system to generate photons for the lasing process. Pump sources include electric discharge, chemical reaction, or possibly another laser. Generated photons from the pump source enters the laser system referred to as an optical cavity which typically consists of two reflective mirrors and a gain medium. The gain medium is where photons interact with the material and undergo a process known as stimulated emission. Stimulated emission is the process of a photon generating an additional photon with identical energy, direction, and phase by passing by an excited electron and causing it to drop to a lower energy state and releasing the identical photon. The gain medium is typically composed from materials with electrons in higher energy states such as rubies and other crystals. Once the photons pass through the gain medium, the photons are back reflected by a mirror and go through the gain medium once more only to be reflected by another mirror. These two mirrors act as an optical resonator where photons are reflected into the same path with the gain medium continuously. This causes the number of photons to increase exponentially in a small period of time until the generated optical power can overcome the reflectivity of one of the mirrors. Once this occurs, the system has begun to lase and is emitting a beam of laser light.

This entire laser system can be created in a semiconductor device similar to a LED. Unlike a LED however, the LD uses a PIN junction rather than a PN junction. The I in the PIN junction represents a region of intrinsic material that can contains a significantly lower quantity of electrons or holes compared to the P and N type materials that it is located in between them. A PIN junction works the same as a LED except that the emitted photons are meant to get trapped inside the intrinsic layer of the device. The intrinsic layer acts as a gain medium that is pumped by the tunneling electrons of the diode. PIN junctions are normally covered with reflective material that form an optical resonator for the intrinsic region. Once enough electricity flows through a LD, the device will begin to lase as the photons generated in the intrinsic region can overcome the reflectivity of the optical resonator. This laser light has a very narrow range of photon energies and is characteristically coherent and share the same phase. The direction of light is diverging at a specific angle in regard to the LD and must be focused by a lens to create a straight beam.

### 3.2.4 Photodiodes

Our computer in our design will be able to detect light feedback by converting light signals into electric signals via photodiodes. Photodiodes are optoelectronic devices that convert photons of light into electrons through the photoelectric effect. Unlike LDs or LEDs that require a PIN junction or PN junction respectively, photodiodes can be structured in either junction style. Additionally, photodiodes can be operated with or without a voltage source which determines the way the device responds to light.

Photodiodes main principle is the photoelectric effect which is essentially the opposite of spontaneous emission. When a photon strikes a surface with enough energy, an electron can be generated in the surface material. In other words, photodiodes absorb light rather than emit light. The more photons with high enough energy strike a surface, the more electrons are generated. These devices operate as current sources rather than a voltage source.

When no bias (voltage) is applied to the circuit containing a photodiode, the device is said to be operating on photovoltaic mode. When no light strikes the surface of the device, the circuit is off. By applying reverse bias to the photodiode circuit, the device is on photoconductive mode. Photoconductive mode has current in the circuit regardless of light which is known as the dark current. The main difference between these modes is the circuit response times with the photoconductive mode being faster but subject to signal noise.

### 3.2.5 Laser Rangefinders

Our design employs a laser rangefinder arrangement dedicated to determining the distance of obstacles directly in front of the camera to aid in navigation. This technology utilizes a laser beam emitted from a laser diode and a photodiode to determine the distance ahead of any solid object in front of it. The distance is calculated either by time-of-flight or triangulation. For time-of-flight, halving the product of the laser beam speed (c, the speed of light) and the time delay of the beam’s activation to the time the photodiode detects the return of the laser beam. Triangulation works in a similar arrangement like the aforementioned method except there is another photodiode in the arrangement which can be used as a reference to the other photodiode to find angles in respect to the reflected laser beam. Via trigonometric properties, the angles of the photodiodes and the distance between the two photodiodes are used to find the distance from the object to the laser diode in-between the two photodiodes, Laser rangefinders are found in a variety of environments and applications including but not limited to:

- 3D Modeling
- Land Surveying
- Aerospace Navigation Systems
- Sports
- Military Weaponry

One Particular application that uses laser range finding is LiDAR technology. LiDAR is an acronym that stands for Light Detection and Ranging. The technology itself is an imaging system that collects three dimensional images. This imaging method uses a pulsed laser as a light source to illuminate a given environment. The time the laser takes from the output of the laser to the system's sensor is measured and used to create a three-dimensional matrix of values. This matrix can be processed into an image that has depth. LiDAR systems are typically mounted on aerospace vehicles to survey large areas of land and map oceans. LiDAR technology was invented in the 1960s shortly after the discovery of the laser itself. The technology was initially only exclusively used in meteorology to measure clouds and pollution in the atmosphere. It did not gain much usage until 1971 where it was used to create an entire map of the lunar surface in the Apollo 15 moon mission. Since then, LiDAR technology has evolved via using various wavelengths, mounted on different devices, and has found new utilities aside from elementary land surveying. LiDAR imaging requires a light source that is coherent, has low divergence, and has a narrow bandwidth of light wavelengths. Laser beams satisfies all these requirements needed for LiDAR illumination. These are required as the photosensor of the system needs to be able to detect a specific wavelength to accurately view the return energy or phase difference of light. A timing system is needed to determine the time difference of when the laser beam was activated and when the photodetector is hit by the laser beam. Additionally, the timing system is used to pulse the laser.

Utilizing a laser rangefinder will allow our camera vision-based device to navigate an environment at faster speeds. Without the rangefinder, the on-board computer must utilize AI to guess distances and will have to waste more computational power and time in order to process these guesses.

### 3.2.6 Laser Projectors

The main laser in our design will be very similar to that of a commercial laser projector for shows. Laser projectors use a very strong laser that is moved around at different angles by a fast-rotating mirror at the output. Projectors can create multiple beam outputs from a single laser by using one or many beam splitters to have individually controllable beams or use diffraction gratings to split a single beam into multiple geometrically bound beams at the output. Some laser projectors have the ability to alter the size of the output beam which is normally achieved through a simple lens system.

A laser beam in the visible wavelength range will be mounted on the top of our device and have the output change shape and direction much like existing laser projectors. Unlike the existing projectors, our laser will use an axial mount similar to a turret rather than a fast-moving mirror to move the beam output direction.

### 3.2.7 Webcams

Webcams are video cameras that communicate over any sort of network. Initially created to watch coffee webcams have become a staple of the internet age. Webcams have served as the inspiration of all video communication of the 21st century and have found a myriad of uses that have taken them further than the simple image streaming devices of 30 years ago. The field of computer vision uses images and videos taken by a webcam to interpret image data; in our project we use webcams for this very purpose to track the motion of the user's pet within a field of view.

### 3.2.8 Robotic Vacuum Cleaner

While our design does not have any cleaning capabilities, it shares many design aspects of a traditional robot vacuum cleaner. The device chassis and motor arrangements are inspired by existing technologies. Our chassis is a short cylinder that has every device housed with it with the exception of the laser projector. Motors in our design are arranged much like a typical three-wheel driven robot vacuum cleaner with the two wheels in the back being used for driving the device forwards and the front wheel being used for steering. The algorithms for navigating an environment were inspired by those used in commercial products.

### 3.2.9 Lenses

Lenses are optical elements that have refractive power called diopters in units of inverse meters which measures how strongly it can spread or converge light rays. If a lens has positive and very high diopters, then it will converge, or focus, incoming parallel light rays very near to the lens. The spot where all the light rays were focused to is called the focal spot and its distance from the lens is called the focal length which is the inverse of the lens's diopters. This means lenses with a short focal length have very high refractive power, and lenses with very long focal lengths have low refractive power. This ideal lens imaging system is shown in Figure 7 where a biconvex lens focuses parallel light rays to a point.

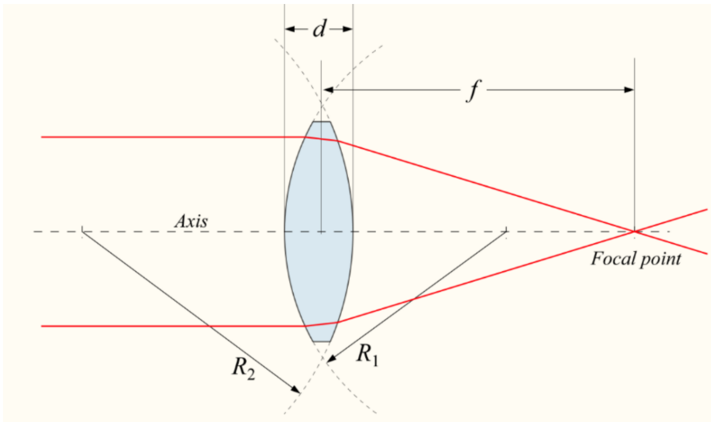

*Figure 7: Positive Lens*

Reprinted with permission from wikipedia

If a lens has negative power, then incoming parallel light rays will diverge and spread out. None of the light rays will ever come into contact with one another, so there is no real focal point for negative power lenses. There only exist virtual focal points for negative power lenses where if all the light rays that were diverged by the lens had its line back projected through the lens, they would all meet at a virtual spot which is the focal length of the negative powered lens as shown in Figure 8. The ideal imaging system of a biconcave lens is shown in Figure 8 that diverges parallel light rays. It is important to understand how a single lens system works so it can be simpler to comprehend how a telescopic lens system works, which involves at least two lenses.

The telescopic lens system is also known as a beam expander where the input, which is the collimated laser beam, will go through a system that has an output of a collimated beam that may be several times larger than the input beam. This is called an afocal system where the object plane is located at infinity and the image plane is located at infinity. We will explore several plausible telescopic lens systems and their characteristics that will best help us choose the best system for our project. Our system should be variable, where the beam of light can change

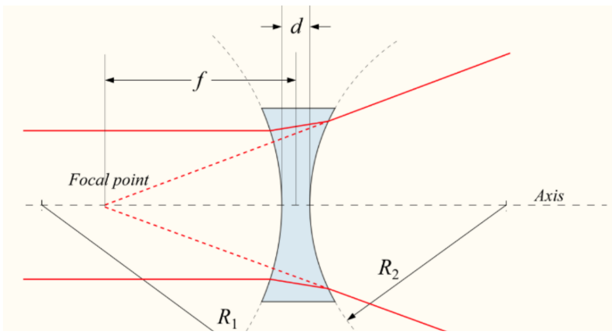

*Figure 8: Negative Lens*

Reprinted with permission from wikipedia its size from small to large that will affect the incoming light on the diffraction grating. In this case it will be best to choose a system that can easily move one of the lenses at will for the desired variability.

Beam expansion has several criteria that it must follow to yield a collimated output beam. The first lens of the system must have a diameter larger than the input beam diameter; for instance, a 12 mm lens diameter will be able to accommodate a 10 mm beam diameter. This is so all the parallel rays of the laser can actually make it through the system and this case is the same for the last lens. The last lens of the system must be at least 90 percent larger than the desired magnified output beam diameter. A 10 mm input diameter that would need 3x expansion for an 30 mm output diameter will need a final lens of at least 33.3 mm diameter.

The Kleperian telescope or beam expander is one of the widely used lens systems that consist of two positive lenses where their focal points are at the same spot while their focal lengths are different as shown in Figure 9. Since the focal spots are located at the focal point, the total distance of the system is the sum of the focal lengths t = f1 + f2. The first lens typically is the more powerful lens where it converges the rays near to it and the second lens is the weaker lens that will collimate the rays from that point, creating the output beam. The definition of the magnification is the ratio of output beam diameter and input beam diameter but is also related to the focal length ratio (f2 / f1) which is essential in its design. A drawback to the system is that it can be considered rather long as the focal length condition is necessary for it to work. For instance, a powerful lens that has a focal length of 50 mm will need a weak lens with a focal of 250 mm for 5x magnification. This means the total length of the system is at least 300 mm.

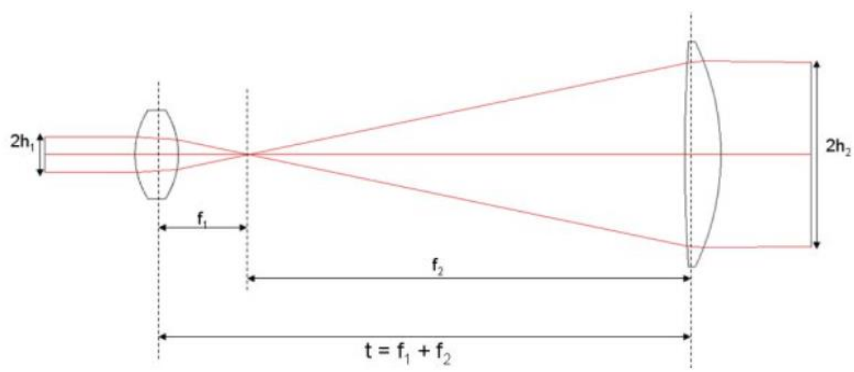


*Figure 9: Keplerian Telescope*

Reprinted with permission from Newport Corporation

The Galilean telescope or beam expander is another popular lens system where it has two lenses one of which is positive, and the other is negative. In Figure 10, the system is set up where there is no fixed focal point in between the lenses so the system has no condition to match focal lengths. Only for maximum magnification will t = f1 + f2, and this allows for the system to be naturally shorter than the Keplerian telescope. The first lens is the negative lens and makes the collimated beam diverge as shown in Figure 8 and Figure 10. The second lens has positive power and will refocus the spreading light back into a collimated beam with a larger diameter. Like the Keplerian telescope, the magnification is dependent on the focal

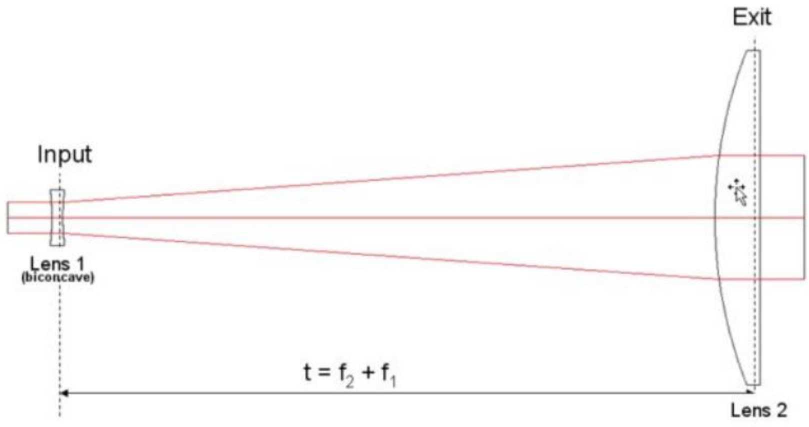


*Figure 10: Galilean Telescope*

Reprinted with permission from Newport Corporation

length ratios of the two lenses, and for variable magnification the telescope length can be less than the combined focal lengths.

There are several brief topics in regard to lens applications such as lens shape, coatings, wavelengths and materials. These topics need to all be considered to yield the best output results from the lens imaging system. Lens shapes for these systems can either be bi-concave or bi-convex and plano-concave and plano-convex. The lens shapes can be seen in Figure 11 and are considered in dealing with aberrations. Aberrations are the errors in focusing such as blurs due to the fact that lenses are not perfect. Plano-convex and plano-concave lenses are used to minimize aberrations when the input or exit beam is collimated, and the curved surface of the lens is facing towards the collimated beam. Bi-convex or bi-concave lenses are used to minimize aberrations for diverging beams.

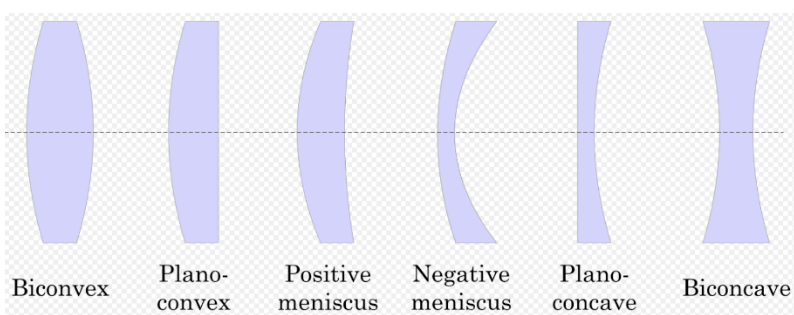


*Figure 11: Lens Types*

Reprinted with permission from wikipedia

*Table 2: Standard AR Coating for Wavelengths*

Reprinted with permission from Edmund Optics

| Standard Broadband Anti-Reflection Coatings | |
|---|---|
| **Coating Description** | **Specifications** |
| $\lambda/4$ $MgF_2$ @ 550nm | $R_{avg}$ ≤1.75% @ 400 - 700nm |
| UV-AR [250 - 425nm] | $R_{abs}$ ≤1.0% @ 250 - 425nm<br>$R_{avg}$ ≤0.75% @ 250 - 425nm<br>$R_{avg}$ ≤0.5% @ 370 - 420nm |
| Laser UV-VIS [250 - 532nm] | $R_{avg}$ ≤1.25% @ 250 - 532nm |
| UV-VIS [250 - 700nm] | $R_{abs}$ ≤1.0% @ 350 - 450nm<br>$R_{avg}$ ≤1.5% @ 250 - 700nm |
| VIS-EXT [350 - 700nm] | $R_{avg}$ <0.5% @ 350 - 700nm |
| VIS-NIR [400 - 1000nm] | $R_{abs}$ ≤0.25% @ 880nm<br>$R_{avg}$ ≤1.25% @ 400 - 870nm<br>$R_{avg}$ ≤1.25% @ 890 - 1000nm |
| Laser VIS-NIR [500 - 1090nm] | $R_{avg}$ ≤1% @ 500 - 1090nm |
| VIS 0° [425 - 675nm] | $R_{avg}$ ≤0.4% @ 425 - 675nm |
| VIS 45° [425 - 675nm] | $R_{avg}$ ≤0.75% @ 425 - 675nm |
| YAG-BBAR [500 - 1100nm] | $R_{abs}$ <0.25% @ 532nm<br>$R_{abs}$ <0.25% @ 1064nm<br>$R_{avg}$ <1.0% @ 500 - 1100nm |
| NIR I [600 - 1050nm] | $R_{avg}$ ≤0.5% @ 600 - 1050nm |
| NIR II [750 - 1550nm] | $R_{abs}$ ≤1.5% @ 750 - 800nm<br>$R_{abs}$ ≤1.0% @ 800 - 1550nm<br>$R_{avg}$ ≤0.7% @ 750 - 1550nm |
| SWIR [900-1700nm] | $R_{avg}$ ≤ 1.0% @ 900 - 1700nm<br>$R_{abs}$ ≤1.5% @ 900 - 1700nm |
| Laser NIR [1030 - 1550nm] | $R_{avg}$ ≤0.7% @ 1030 - 1550nm |
| 2µm BBAR [1900 - 2100nm] | $R_{avg}$ <0.5% @ 1900nm - 2100nm<br>$R_{avg}$ <0.25% @ 2000nm - 2100nm |

Anti-reflection (AR) coating can be applied to lenses to minimize reflection and power loss but will become necessary if the power loss is too substantial. AR coatings can get expensive and will most likely apply to our project if the reflection loss is too high as we prototype the devices. Table 2 is for reference for if AR coating must be considered when it comes to that time. AR coating is highly dependent on wavelength of the light, and the index matching of the coating to the lens plays a large role in its expense. It is best to choose lenses that already have available AR coatings at our needed wavelengths.

## 3.2.10 Diffraction Gratings

Diffraction gratings operate on the principle of interference of light which can only happen with coherent sources such as lasers. Interference is derived from the superposition of light where waves will interact with each other and produce constructive or destructive interference where these patterns can be examined in

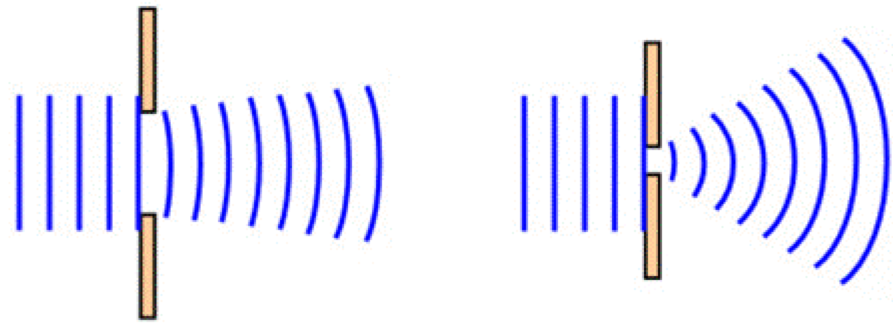

*Figure 12: Diffraction based on Aperture Size*

Reprinted with permission from Alternative Physics

far-field optics. These patterns can be most easily explained by the wave-like nature of light. Since light behaves like a wave, when it passes through an opening that is relatively small the light will diffract. Diffraction is the tendency for waves to disperse and bend its path more as it comes near an object as shown in Figure 12; the smaller hole will bend the wave more than the larger hole. This bending becomes more apparent as the hole's size gets closer to the wavelength of the light. The concept of diffraction is the reason that interference patterns show up when laser light comes into contact with a grating which consists of many miniscule holes or slits near adjacent to each other.

As laser light comes into contact with a diffraction grating, the equation below can describe the pattern:

$$d \sin \theta_m = m\lambda \quad (1)$$

Where d is the spacing between slits in the grating, θm is the angle of the order from the center, m is the order integer which can be related to the height z, and λ is the light wavelength, and can be visualized in Figure 13. Sin(θ) can be simplified as the height z over the distance to the screen L:

$$d \frac{y}{L} = m\lambda \quad (2)$$

Where so key relationships between the grating, distances, and wavelengths can be shown. Something to note before considering equation (2) is that the grating spacing alters the intensity pattern best illustrated in Figure 14. As the gratings become higher frequency (slits per unit distance), the spread of the light narrows and becomes more focused at its orders. This increases distance between the bright spots so the orders m that is linked to the height of the screen is a function of the grating spacing d. The diffraction grating frequency is the most important parameter when choosing a grating because it will affect the complex patterns we can display. For our project wavelength will be fixed, but L will be changed frequently. This may not pose a problem as its ratio with the height y will only change slightly and can be approximated to be a constant number. Only when the

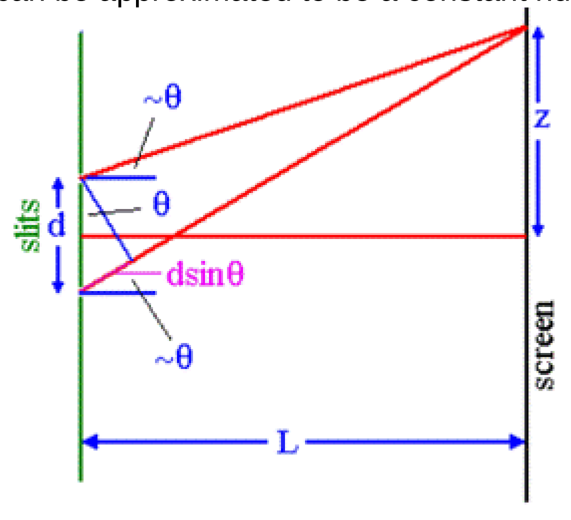


*Figure 13: Diffraction Grating Effect*

Reprinted with permission from Electron6

L is very short (the laser is pointing to an object very close to it) will it need to be considered, but this is not a concern of our project.

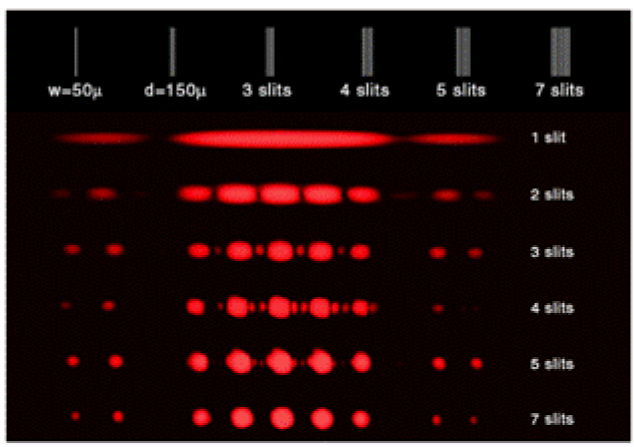


*Figure 14: Diffraction Grating Intensity Patterns*

Reprinted with permission from Electron6

## 3.2.11 Polarizers

Optical polarizers are devices used to change the propagation orientation of light that passes through a device. These devices work on the principle that light cannot only be interpreted as a photon but a wave as well. If we view light as a wave, we can use the basis that light is an oscillating electro-magnetic wave that propagates in free space. EM waves contain a strong electric field component and a weak magnetic field component that oscillate in a trigonometric pattern that corresponds to a sinusoidal or cosine functions. The two fields propagate in the same direction but are tangential to each other in space. This oscillation pattern can have many variations such as amplitude, frequency, wavelength, and phase shift. These variations give light unique orientations in the direction in which in propagates. They can be visualized by a unit circle where the angle on the circle corresponds to the direction the light faces. Typically, the electric field is used when referring to light polarized at an angle due to how much more significant it is compared to the magnetic field. Due to the nature of oscillating trigonometric functions, there is symmetry along angles corresponding to a 180° difference. In other words, light

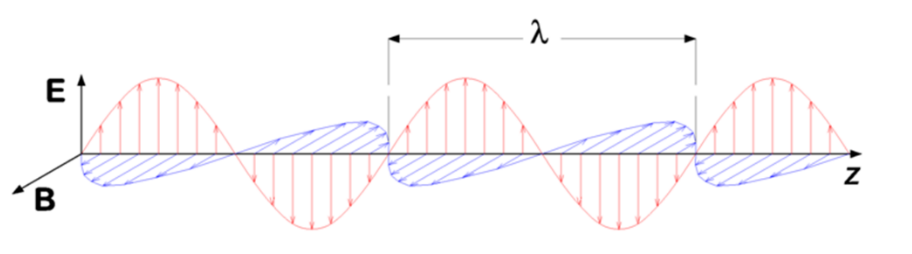


*Figure 15: Standard EM Wave*

that is oriented at 90° also propagates at 270°.

Orientations of light fall into three specific categories: Linearly polarized, circularly polarized and elliptically polarized. Linearly polarized light propagates at a specific angular orientation with a given amplitude. An example would be light in a laser scanner being oriented at 45°. Circularly polarized light describes light that rotates in angular orientation in a perfect 360° circle with the same amplitude. Elliptically polarized light is like circular polarization except the amplitude varies while completing a circle causing an ellipse pattern. Light emitted from a standard light source typically is a collection of all the polarizations and is referred to as randomly polarized light.

Light sources do not emit polarized light with very few exceptions. If we need to use polarized light, we can use polarizers to create polarized light from randomly polarized light or re-orient polarized light in a different polarization. Linear polarizers take incident light and transform it into linearly polarized light at the angle the polarizer itself is angled at. If the light incident on the linear polarizer is not linearly polarized, the light that passes through the polarizer is oriented at the angle of the polarizer and has its total optical power halved. If light incident on the polarizer is already polarized in the same angle as the polarizer, nothing changes. If light incident on the polarizer is linearly polarized and the angle of light does not match the angle of the polarizer, the light passing through the polarizer has the angle of the polarizer and has an optical power corresponding to Malus's law. Malus's law is the following:

$$I = I_0 \cos {\theta_i}^2$$

Where I0 is the incident optical power on the polarizer and θi is the angle of the polarizer subtracted by the angle of the incident linearly polarized light.

Light polarizer technology is used in several real-life instances. The most common use of optical polarizers is in commercial sunglasses. Sunglasses that are labeled as polarized simply have a polarizer film on the lenses. Sunlight is naturally randomly polarized so a polarizer would half the intensity of the light on the sunglasses. Additionally, polarizers eliminate optical glare, or the intense white light seen on bodies of water and other highly reflective surfaces. Polarizers eliminate glare by simply filtering out this glare light that is linearly polarized. Another use of polarizers is in liquid crystal display (LCD) screens. Light emitted from LCDs are polarized. This is done in order to control the output intensity of generated light.

APES can use optical polarizers in the event where the laser light emission optical power needs to be controlled. This can be done because laser emission is one of the very few existing light sources that emit linearly polarized light. Given the angle at which the laser light is oriented at, the laser optical power, and the desired output power, Malus's law can be rewritten to find the specific angular orientation the polarizer must be at to yield our desired optical power. Controlling the optical output power can allow us to prevent photodiode oversaturation and meet laser power safety standards if our output power is too high.

## 3.2.12 Gyroscopes and Processing Methods

The APES will utilize a combination gyroscope and accelerometer to measure its attitude in real space. To do this the raw data from this component must be processed in a way that will return the angle of the device relative to a plane. Accelerometers output the acceleration of the device in three axes. Given this information it is relatively simple to extract the angular position of the device via Pythagorean's theorem. The gyroscope is a bit more complicated to process.

A gyroscope returns vector data based on angular speed when the device is moved over time. This means that in order to extract the angle from this sensor, we must perform an integration over time.

With angle data from both the accelerometer and the gyroscope, the APES can then perform a weighted average of the two data points to both help eliminate the drift from the gyroscope and to correct for any other error from either the accelerometer or the gyroscope.

## 3.3 Strategic Components and Part Selection

Over the years, electronic components have become more accessible to the general public via cost and size reduction. This has led to the ever-expanding community of hobbyists that design and build open-source electronics projects. These projects and the components used in them have made the job of a prototyping engineer much simpler since nearly any electrical component imaginable can be found on an easy-to-use module ready to integrate with any microcontroller, microprocessor, or other development platform.

## 3.3.1 Controllers

**Raspberry Pi**

The microcontroller and microprocessor serve as the brain of the embedded system and interprets sensory data and relays information to the rest of the system based on their input. For our project we will be using the raspberry pi 3b as the microprocessor responsible for performing the calculations necessary for the webcam to act as visual sensor for the project, while also driving the servo that will adjust the laser display in response to the webcams visual input. It will communicate via serial bus to an Arduino microprocessor which will be responsible for the optic sensory data used in navigation and for driving the motors that the system will use to propel itself.

There are multiple versions of the Raspberry Pi available on the market, each more advanced than the last. The deciding factor for which model to use was chosen based on a cross analysis of performance and cost. For the project we considered three versions of the Raspberry Pi to act as the main data processing unit of the toy: The Raspberry Pi 3B, the 3B+, and the 4. The Raspberry Pi 3 Model B was the first of the third generation Raspberry Pies and was explicitly made with the act of camera vision and touch screen connectivity. Along with a quad core processor that allows for in depth calculations done with increased speed when in comparison to past models of the microcontrollers. Important to us is an explicit CSI camera port for connecting a Raspberry Pi camera and an entire GB of memory for our system to work with when processing image data. Memory is important because the number frames the controller can analyze from the camera quickly improves the ability of the system to detect motion.

The Raspberry Pi 3B+ maintains the same mechanical footprint as the Pi 3B but includes upgrades in its communications ability. Compared to the 3B the B+'s primary advantage lies with its processor. At 1.4GHz the 3B+'s BCM2837 processor preforms at a higher speed than the similar 1.2GHz processor shipped with 3B. The B+ also includes the Cortex-A53 ARM microarchitecture which, while weaker than the Cortex-A57, provides a powerful instruction set to the microprocessor while being more energy efficient. However, this change while on paper may seem significant does not provide much of a real-world advantage to B+ when it comes to computational power. Furthermore, the additional improvements to this increment on the 3B including, Gigabit Ethernet, dual band Wi-Fi capabilities, HDMI support, and power over Ethernet, do not offer any benefit to our project. With a slight price difference of about six dollars, $33.92 vs $39.99 when compared with the 3B, the 3B would seem to be the better option.

But what of the Raspberry Pi 4B? The 4B offers much more substantial improvements going from the Raspberry Pi 3 series. At the center of any processor is the processor itself, and in the Pi 4B's Case the BCM2711 Cortex-A72 offers substantial improvement to the microprocessor. The new A72 test at almost 4 times faster than the previous A53 and the processor runs at 1.5 GHz compared to the 1.4 of the A53. While there are other numerous improvements such as Bluetooth 5, and a newer GPU, the only other improvement that relates to our project is the multiple sizes of RAM available to the 4B. While the 3B and + only comes with 1GB the 4B staying true to its name offers up to 4GB of RAM built into the board. As previously discussed, the amount of memory available to our system allows for better results in the motion tracking software. However, with an increased price of the $59.99, do the increases in practical performance actually equate to a doubling of the cost.
Table 3 summarizes these comparisons:

*Table 3: Relevant Microprocessor Specification Comparison*

| **Processor** | **Raspberry Pi 3B** | **Raspberry Pi 3B+** | **Raspberry Pi 4B** |
|---|---|---|---|
| **CPU** | BCM2837@1.2GHz | BCM2837@1.24Hz | BCM2711@1.5GHz |
| **Memory** | Up to 1GB | Up to 1GB | Up to 4GB |
| **Weight** | 2.82 ounces | 2.25 ounces | 1.76 ounces |
| **Price** | $33.92 | $39.99 | $59.99 |

**Microcontroller**

The intended application of a microcontroller is to control the navigation and range finding aspects of the toy. The Raspberry Pi will communicate with the Arduino as to when the toy should move and when the toy should be stationary. Given this information, the selected microcontroller must include at most four GPIO pins capable of pulse width modulation (PWM) control as well as six additional GPIO pins.

There is no shortage of options when it comes to a microcontroller and the main factors that the decision comes down to are how well does the programmer know the device and how well does the controller meet the needs of the project without being excessive. The two main microcontrollers that fall under this category are the ATmega328 and the MSP430G2553. The ATmega328 is a microcontroller commonly found on Arduino development boards and has very simple software setup. The MSP430G2553 is what has been taught in many engineering courses. The software setup is more complicated, but the team has much more experience working with it. In

Table 4, the specifications of each microcontroller are compared.

Given these comparisons, the ATmega328 fits the bill better than the MSP430G2553. This is a very common microcontroller and can be found in many Arduino development boards including the UNO, MINI, NANO, PRO, FIO, ETHERNET, and LILYPAD [2]. This versatility allows for a great deal of adaptability which may be necessary during the testing process however, the number of features is not excessive. The ATmega328 has a faster clock speed which is crucial when analyzing data that controls safety features of the toy. The ATmega328 also includes the correct number of PWM capable pins. These combined with how common the board is means that the production cost is decreased since a development board using the ATmega328 is already owned by the group and the programmer is very familiar with the Arduino Integrated Development Environment (IDE). These factors make it clear that the ATmega328 is the correct microcontroller for this application.

*Table 4: Microcontroller Specification Comparison*

| Specification | ATmega328 | MSP430G2553 |
| --- | --- | --- |
| **Operating Voltage** | 1.8-5.5 V | 1.8-3.6V |
| **Operating Temperature** | -40°C to 85°C | -40°C to 85°C |
| **Max Clock Frequency** | 20 MHz | 16 MHz |
| **Memory** | 32 KB Flash, 1 KB EEPROM, 2 KB SRAM | 16 KB Flash, 0.5 SRAM |
| **Analog I/O** | Input | Both |
| **Digital I/O** | Both | Both |
| **GPIO Pin Count** | 20 | 20 |
| **PWM Capable Pins** | 6 | 3 |
| **Bit Count** | 8 | 16 |
| **Low Power Mode Availability** | Available | Available |
| **Power Consumption** | Active Mode: 200μA@1MHzOff Mode: 0.1μA | Active Mode: 330μA@1MHzOff Mode: 0.1μA |
| **Price** | $16.06 (Free: Already Owned) | $19.83 (Free: Already Owned) |

## 3.3.2 Laser Diodes

It is imperative to know what power and wavelength is needed for the situation when choosing laser diodes. In the case of our cat toy, we have two specific utilities for lasers: The adjustable show laser and the laser rangefinder. The show laser is designed to be powerful enough to be seen in broad daylight but not too powerful that would harm the cat or any other living creature in the vicinity. Additionally, the wavelength has to be viable to both cats and humans.

According to the United States Food and Drug Administration (USFDA or FDA), lasers become hazardous to the human eye after long exposure times when classified as class IIa or class II. While there exists no governing authority for laser safety for cats or any other pets, it is safe to assume that we would like to prevent any harm to any cat or persons. We can assume that a class II laser can be safe to use knowing that this particular laser system was designed to move around and will lose power when put through a lens system and if put through a diffraction grating. A class II laser's output is limited to a maximum of 5 mW peak power. Knowing this limitation, we can now decide on our show laser diode wavelength.

The show laser must not only be visible to humans but to cats as well. Cats are sensitive to green color wavelengths (495 nm – 570 nm) much like humans. However, they lack the sensitivity to interpret any wavelengths of higher or lower than the green range properly. It would then be in our best interest to find a laser diode within the green wavelength range. One of the most common commercially available green laser diodes happens to be at 532 nm wavelength which is in our range and is rather affordable than other green wavelengths. After considering all factors, it was decided that a 532 nm class II laser would be used for the show laser.

Using the determined limitations for our show laser, three options for diode were found. Our first option comes from Thorlabs: The DJ532-10 532 nm solid state laser diode. This package includes the diode with three pins for the standard current flow and a photodiode pin along with a heat sink for the entire package. Ideal operating optical output power is 10 mW with a maximum optical power output at 20 mW for this device. While this is significantly higher than our allotted safety output of 5 mW, the power difference can be adjusted for with a polarizer. The cost of the DJ532-10 device is $160.15. Our second option found was the CW532-005 532 nm laser package from Roithner Lasertechnik GmbH. This diode package contains a driver for the device unlike the Thorlabs package. The maximum optical output power of this device is rated at 5 mW. This diode package is offered at a price point of $40.20. Our final option found was the 532nm Green Line laser module from Light88. This diode package is exactly like the package from Roithner Lasertechnik GmbH from the power output to the included driver. However, this package retails at a price of $22.69 per piece. Given these options and our safety limitations, it was decided to go with the 532nm Green Line laser module from Light88. This package was chosen for meeting all safety limitations, the inclusion of the diode driver, and the price point being significantly lower than all the rest.

For our laser rangefinder, an entirely different laser diode had to be considered. The rangefinder laser will be actively used for navigation and could be distracting if the laser beam is visible. Also, the laser needs to be powerful enough to have a detectable return beam and not powerful enough to cause any eye damage if accidentally reflected into a cat or human eye. Knowing the FDA safety guidelines, we must limit our laser to a class II laser at 1 mW peak power output. The laser's wavelength must be outside of the visible spectrum (380 nm – 700 nm) and must be able to be picked up efficiently by the photodiodes in the detectors whilst not being able to conflict with our IR LED output (940 nm). Most commercially available photodiodes are particularly sensitive to light in the near infrared region (800 nm – 2,500 nm). One particular wavelength that is rather sensitive to photodiodes and is far enough from the LED output in terms of wavelength is a 1064 nm laser diode. We can effectively choose a 1064 nm class II laser diode for our rangefinder laser after considering all factors.

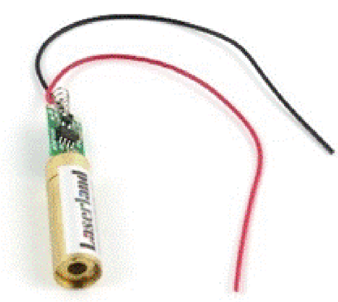

*Figure 16: 532nm Green Line Laser Module from Light88*

Reprinted with permission from: Laser Lands

Using the determined limitations for our laser rangefinder, three options for the diodes were narrowed down. The first considered diode package is from Thorlabs: The M9-A64-0200 1064 nm solid state laser diode. This particular package includes the diode with three pins for the standard current flow and a photodiode pin to measure back reflection. Ideal operating optical output power is 200 mW for this device. While this is significantly higher than our allotted safety output of 5 mW, the power difference can be adjusted for with a polarizer. The cost of the DJ532-10 device is $452.32. Our second option found was the 10mW, 1064nm DPSS Pointing Laser package from Edmund Optics. This diode package contains a driver for the device unlike the Thorlabs package. The maximum optical output power of this device rated at 10 mW. Like our Thorlabs option, this extra optical power can be adjusted using a light polarizer. This diode package is offered at a price point of $325.00. Our final option found was the 1064nm 50mW Laser Diode Module from CivilLaser. This diode package is like the package from Edmund Optics as it includes a diode driver and is above our safety optical power level. This raised optical power can still be dealt with a polarizer. However, this package retails at a price of $179.00 per piece. Given these options and our safety limitations, it was decided to go with the 1064nm 50mW Laser Diode Module from CivilLaser. This package was chosen for the inclusion of the diode driver and the price point being significantly lower than all the rest.

*Figure 17: 1064nm 50mW Laser Diode Module*

Reprinted with permission from CivilLaser

# 3.3.3 Camera

While the market for webcams is borderline saturated, for our project we primarily focused on three main metrics when it came to a webcam: size, we intend to have the camera mounted to the toy thus it cannot be an obstruction; and image/video quality, this covers the general quality of image the Camera is able to output and includes the framerate, resolution, and noisiness of the image. We considered three cameras based on these criteria: the Dorhea Mini Cam Module 5, the Raspberry Pi Camera Module V2, and the Logitech C270 Webcam. The C270 from Logitech was the first camera researched to be part of the project. It stood out as an all-purpose webcam for a cheap price that utilized universal serial bus as its input/output interface. Looking at the specs we used this camera as a baseline for what our camera should do. The camera has a fixed resolution 1280x720p which should be a good resolution for object detection however having a max fps of 30 frames means that the total amount of data accessible to the system is limited. While it may be adequate further testing would be needed to determine if it would serve our system well. The size and shape of the camera would present a problem. At over 6 ounces the Logitech is the heaviest camera and due to its shape, pictured in Figure X, would run the risk of adding additional weight at certain points and setting the machine off balance. Finally, the price of the C270 came out to be $39.99, making it the most expensive camera we considered.

The Raspberry Pi Camera Module V2, is a Pi cam developed in house by Raspberry Pi. Its most attention-grabbing feature along with the Dorhea was its compatibility with the Raspberry Pi, coming with its own slot directly on the SOC the pi cameras have a faster transfer rate of data to and from the SOC. Another stand out feature is the size of the camera weighing only .1 ounces and being not even an inch in length and width, the camera could be mounted to virtually anything without much obstruction to the function of the device. Compounding both the Dorhea and Raspi Cam come with screw holes that would allow the camera to be fastened to the project in a way traditional webcams would not allow; Figure 19 shows the RPCM-V2.


*Figure 18: Logitech C270*



As far as quality goes the both the Dorhea and Pi are able to capture footage at 60 fps at 720p meaning their image quality is twice that of the Logitech. The Pi cams also feature multiple resolutions meaning we can adjust between resolution and fps to determine which best suits the projects need for quality and speed. The RPCM-V2 does feature a higher still image resolution at 8MP vs the 5MP featured in Dorheas, however this feature is inconsequential when compared to the difference in prices. While the offering only marginal improvements the RPCM-V2 cost $22.59 compared to the Dorhea OV5647 which is priced at $8.39. The RPCM-V2 performs at an extremely higher capacity than the Logitech C270 at nearly half the price, while the Dorhea’s camera performs nearly as well at less than a quarter of the price! The differences in cameras are summarized in Table 5. We decided upon Dorhea due to seeing no major differences between the two Pi cams due to the price/effectiveness making for a very efficient combination for our project.

*Table 5: Relevant Camera Specifications*


*Figure 19: Raspberry Pi Camera*

Reprinted with permission from wikipedia

| Camera | C270 | RPCM-V2 | Dorhea OV5647 |
|---|---:|---:|---:|
| Weight | 6 ounces | .1 ounces | .2 ounces |
| Max Res | 1280x720 | 1920x1080 | 1920x1080 |
| FPS | 30 | 60 | 60 |
| Price | $39.99 | $22.59 | $8.39 |

# 3.3.4 Motors

Motors serve multiple purposes in the operation of the toy. There are multiple types of motors available and it was necessary to determine which type of motors was appropriate for each application. The two main categories of motors are divided into AC and DC motors. Since this toy will run on battery power, it is clear that AC motors will add significant unnecessary complexity to the project. AC motors also have significantly more complex speed regulation requirements; a factor that weighs heavily on the application of the motors.

**Drive Motors**

One of the motors applications is to be the main source of propulsion for the toy. Given the three wheeled design of the toy, two independent motors will be used to power the drive wheels. These motors will require a sufficient amount of torque to propel the toy across multiple different surfaces including carpet as well as a high enough RPM to navigate spaces at a reasonable speed. The size of the motor is another consideration for the sake of compactness.

Some common options for robotics hobbyists include the DC gearbox or “TT Motor” shown in Figure 20 and a standard 130 size hobby motor. The specifications for these motors are shown in Table 6.

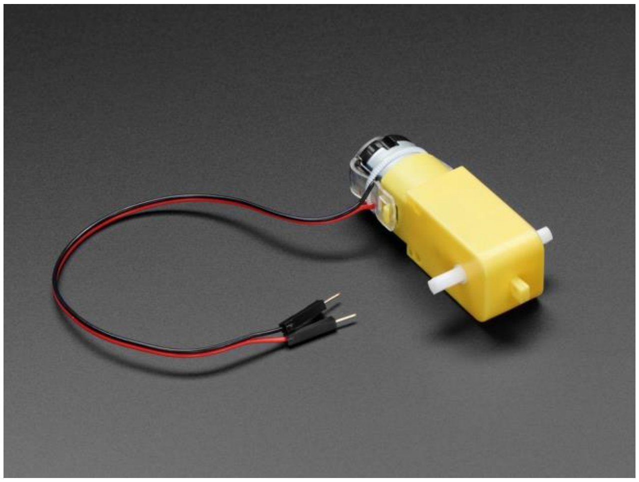

*Figure 20: DC Gearbox Motor "TT Motor"*

Reprinted with permission from Adafruit

*Table 6: Motor Comparison*

| Specification | TT Motor | 130 Size Motor |
|---|---|---|
| **Operating Voltage** | 3-6V | 4.5-9V |
| **Stall Torque** | 800g*cm | 10g*cm |
| **No-Load Speed** | 120-250 rpm | 9100 ±1800 rpm |
| **Dimensions** | 70 x 22 x 18mm | 27.5mm x 20mm x 15mm |
| **Gear Ratio** | 1:48 | N/A |

It is clear that the TT motor is much better suited to the task of driving toy than the size 130. While the size 130 is much smaller in footprint than the TT motor, the TT motor has the advantage of already incorporating a gearbox into the design that allows for significantly better torque than the size 130. There is also the fact that the motor shaft on the TT motor is compatible with a range of wheels available. This means that wheel selection and mechanical design will be simplified.

**Telescopic Lens Motor**

The main ‘show’ laser for this toy will shine through a pair of convex lenses in order for the toy to have the ability to change the size of the dot projected on the ground. This is to be accomplished by securing one lens and attaching the second to a rack and pinion type apparatus. This will be actuated with a DC Motor, size 130. Given there is no requirement for excessive torque or precision with this application, the size 130 will be sufficient.

**Diffraction Gratings Wheel Motor**

Not only will the show laser shine through a pair of convex, telescoping lenses as mentioned above, but it will also shine through a diffraction grating to change the shape and pattern of the laser output. This diffraction grating will be mounted on a wheel with a selection of different gratings. These will be cycled through the use of a stepper motor.

A stepper motor was chosen for this application because unlike a regular DC motor, it works by dividing each rotation into sections or steps. The motor can be directed to spin a specific number of steps to a desired location. Unlike most common servo motors, the stepper motor can continue to rotate more than half a rotation.

The stepper motor and driver we plan to use for this are the 28BYJ-48 step motor and ULN2003 driver. These were selected for their ease of integration with the ATmega328 and their small size. Since the gratings and grating wheel will both be very lightweight, torque should not be an issue.

**Motor Driver**

These motors cannot be used by connecting them directly to the central processor. Instead, they must be connected to a motor driver which is controlled by the processor. This motor driver serves the purpose of regulating the voltage input into the motor and protecting the processor from both the noise created by the running of a DC motor as well as any surge of back current that can be created by the spinning of the motor through outside force.

One of the most popular motor drivers is the Dual H Bridge L298N Motor Drive Controller shown in Figure 21.

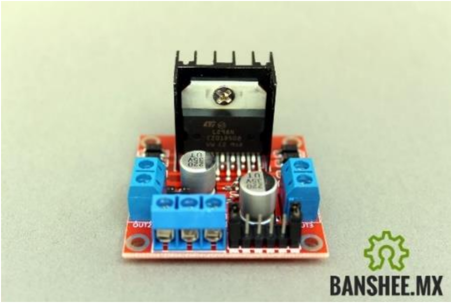


*Figure 21: Dual H Bridge L298N Motor Drive Controller*

Reprinted with permission from Banshee.mx

This motor controller provides a stable and reliable connection between the processor and the motors, a large filter capacitance, an after-flow protection diode, and the ability to drive two DC motors individually. These features coupled with the small size make it a clear choice for use in this product.

### 3.3.5 Servos

Unlike traditional DC motors, servo motors do not rotate continuously. Instead, servos move their motor shaft to a precise angular location based on the value received from the controller.

This toy includes the ability to pan and tilt the main laser independently from the main body of the device. This will be achieved through the use of two servo motors, one for horizontal motion or panning and one for vertical motion or tilting. The combination of these servo motors will allow the laser to be directed anywhere within a 180° horizontal and 150° vertical cone. For this, the product will employ two MG90S 9g Micro Servos.

This servo was chosen over its similar counterparts because it includes metal gears which will prove to be much more durable than the plastic used in most servos. The weight of the laser apparatus combined with any jostling the toy will experience during movement dictate the need for a robust system.

### 3.3.6 Gyroscope

Since this product is a cat toy that includes a laser pointer there is always the possibility that the toy will become inverted. To ensure the safety of the cat and anything else in the vicinity, the toy needs to be able to deactivate the laser upon inversion. This will prevent the laser from being shone directly into the eyes of any potential user. In order to achieve this, the toy must be able to determine its orientation. The best way to evaluate this is with a gyroscopic measurement system.

There are many options that can achieve this measurement, each with their own pros and cons. This toy does not need to track acceleration or its orientation within the Earth's magnetic field so in general accelerometers and magnetometers are not necessary. However, it is very difficult to find sensor arrangements these days that do not include at least one of these other peripheral chips. With this being said, there are a few options to consider shown in Table 7.

*Table 7: Gyroscope Comparison*

| Specification | LSM6DS33 | LSM6DS33 + LIS3MDL |
|---|---|---|
| **Degrees of Freedom** | 6 | 9 |
| **Gyroscope** | Yes | Yes |
| **Accelerometer** | Yes | Yes |
| **Magnetometer** | No | Yes |
| **I2C Interface** | Yes | Yes |
| **SPI Interface** | Yes | Yes |
| **Price** | $5.95 | $9.95 |

Clearly, the LSM6DS33 is the better choice for this toy. This breakout board includes a gyroscope and accelerometer each with 3 axes allowing for 6 DoF. Including both SPI and I2C communication options, this is an ideal gyroscope-accelerometer combination sensor no matter the controller. The magnetometer and the increase in price for the LSM6DS33 + LIS3MDL take it out of the running. Despite having the exact same size, the magnetometer is just extra cost that will not be utilized.

## 3.3.7 Navigational Sensors

**LEDs**

Unlike our laser diodes, LEDs do not have any particular restrictions in regard to safety for humans or pets. The purpose of the LEDs are to aid the device in avoiding obstacles around it that it cannot see with the front facing camera. We need to use a wavelength that is not visible and has the ability to be effectively detected by a photodiode. The near infrared (NIR) region of the light spectrum is not only invisible to humans but to cats as well. Common photodiodes have particularly sensitivity to the NIR region as well. The most common infrared LEDs are 850 nm output which lies in the NIR region and is cost effective. This wavelength does not interfere with the laser rangefinder wavelength of 1064 nm either. Since the purpose of the LEDs are only to check small distances from the device, the power output can be relatively small in the order of 10 mW. The most effective LEDs for the device would therefore be 850 nm LEDs similar to that shown in Figure 22 that emit at least 10 mW of optical power.

*Figure 22: 850 nm LED*

Reprinted with permission from  wikipedia

After sorting through many LED options, it was decided to use the VSLY5850 850 nm High Speed LED from Vishay Semiconductors. The price of an individual LED is $0.93 while being sold in packages of 100 units each. This LED device emits 850 nm light as needed by our APES. They emit optical power up to 600 mW which is beyond our need of only 10 mW but, they can be operated at lower currents for lower optical power emission. This LED model was chosen due to its relatively low cost and excellent performance values that exceed our necessities.

**Photodiodes**

When choosing a photodiode to use for the design, it was necessary to evaluate the responsivity of the device in accordance with the desired wavelength we will use it with. Additionally, this semiconductor device absorbs light rather than emit it which makes safety less of a concern. In the case of the laser rangefinder, we need a photodiode that is sensitive to 1064 nm wavelength and has a relatively fast response time. Most photodiodes are typically sensitive to the NIR range of wavelengths which 1064 nm falls in to. The photodiode would be more effective if contained in a can diode packaging to restrict the amount of light that reaches the semiconductor material. With all these factors considered, a basic silicon photodetector housed in a can diode package such as that shown in Figure 23 is chosen as the laser rangefinder detector.

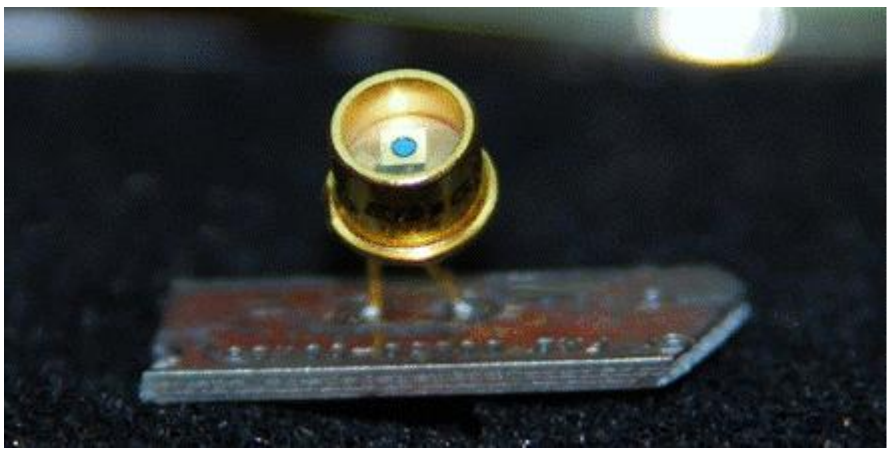

*Figure 23: A Photodiode in a Can Package*

Reprinted with permission from wikipedia

For our rangefinder photodiodes, our research found three specific high-performance devices for the job. First, we found the FDS100 - Si Photodiode from Thorlabs. This device features a very fast rise time of 10 ns which is excellent as it can boost our rangefinder's operating speed. The wavelength response range is 350 - 1100 nm which our 1064 nm laser wavelength falls into. This device costs $14.94 per unit. Our second option for the rangefinder photodiodes was the LSSPD-U1.2 UV Silicon PIN photodiode from CivilLaser. This device features a rise time of 8 ns which is even faster than the device from Thorlabs. The responsivity range is 200-1100 nm for the CivilLaser device. This range is larger than the Thorlabs device but is not usable since we are focused on the 1064 nm response. Once unit from this manufacturer costs $13.00 per unit. Our final option considered was the Hamamatsu S5972 IR + Visible Light Si PIN Photodiode. The device features a rise time of 2 ns which is the fastest response time of all the considered photodiodes. This device has a response spectra of 350 – 1100 nm which includes 1064 nm. Cost of the Hamamatsu device is $15.67 per unit. After careful consideration, the CivilLaser LSSPD-U1.2 UV Silicon PIN photodiode was chosen for its low cost and effective rise time as well as including a response to the 1064 nm wavelength.

For our LEDs, we only need a crude photodiode that can sense the presence of 850 nm in a very small distance directly in front of it with a relatively slow response time. With this in mind, we can simply choose a cheap photodiode that is sensitive to the LED wavelength and is as compact as the LED. The cheapest 850 nm photodetector comes in a compact package that is very similar to the packaging of a standard LED.

After sorting through many LED package photodiode options, it was decided to use the PIN Silicon Photodiode Type OP999 LED from OPTEK. The price of an individual LED is $0.11 while being sold in packages of 10 units each. These photodiodes have peak response to 850 nm which matches are LED wavelength as needed. They have a rise time of 5 ns which a lot faster than what is required for its fairly simple task. This particular photodiode model was chosen due to its relatively low cost and excellent performance values that exceed our necessities.

## 3.3.8 Other Non-electrical Parts

This section includes the selection of a number of essential components that are mechanical in nature including the drive wheels, front wheel and servo mount.

**Drive Wheels**
There are four main options for the drive wheels: the Adafruit skinny wheel, thin wheel, chunky wheel, and Stemedu wheel. These are shown in Figure 24 and their attributes are compared in Table 8.

*Table 8: Wheel Attribute Comparison*

| Wheel | Diameter (mm) | Thickness (mm) | Tread Material |
|---|---|---|---|
| **Skinny** | 59.8 | ~9 | Silicone |
| **Thin** | 65 | 18 | Unknown |
| **Chunky** | 63 | 29 | Silicone |
| **Stemedu** | 65 | 28 | Unknown |

The skinny wheel is the thinnest which means it is the easiest to incorporate into the overall design however it also leads to the most potential instability. The silicon treads allow for good traction across different surfaces. The small diameter limits the top speed of the toy.

The thin wheel has the best overall dimensions striking a good balance between stability and space consumption however the unknown tread material means that the traction and noise of the wheels on different surfaces is in question.

The chunky wheel is the thickest wheel and has silicone treads which means it has the best stability and overall traction. The thickness of the wheel does mean that it would be the most difficult to incorporate into the design.

The Stemedu wheel represents the most commonly available wheel for the TT motors. With dimensions comparable to that of the chunky wheel, it offers good stability at the cost of space consumption. The unknown tread means that the traction across different floors and noise are unknown variables.

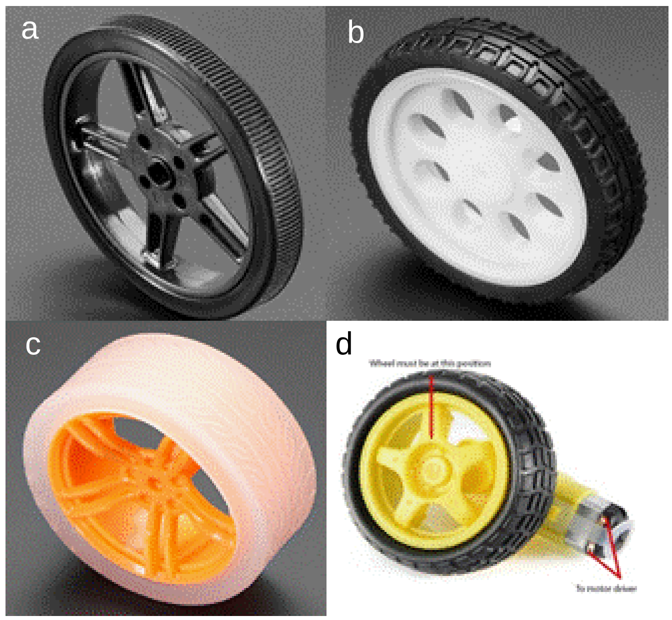


*Figure 24: a) Skinny Wheel b) Thin Wheel c) Chunky Wheel d) Stemedu Wheel on TT motor*

Reprinted with permission from Adafruit and Teachmemicro.com

**Front Wheel**

The three wheeled design of the toy calls for a passive wheel at the front of the chassis. This wheel must be able to rotate freely in all directions to accommodate the steering method of two independent back drive wheels. To best accomplish this, a caster wheel is needed such as the Supporting Swivel Caster Wheel from Adafruit shown in Figure 25.

*Figure 25: Supporting Swivel Caster Wheel*

Reprinted with permission from Adafruit

This caster wheel has a 1.3” diameter making it small enough to not upset the balance of the toy and impede stability but large enough that traversing different surface textures will not be an issue.

**Servo Mount**

Having a reliable mount for the main laser of the toy is a key element to ensure smooth and safe operation. Thus, the GHH PT Pan/Tilt Camera Platform shown in Figure 26 was selected. This apparatus is designed to house the MG90S 9g Micro Servos selected for this product. With an easily customized top mounting surface, it will be not be an issue to attach the needed hardware.

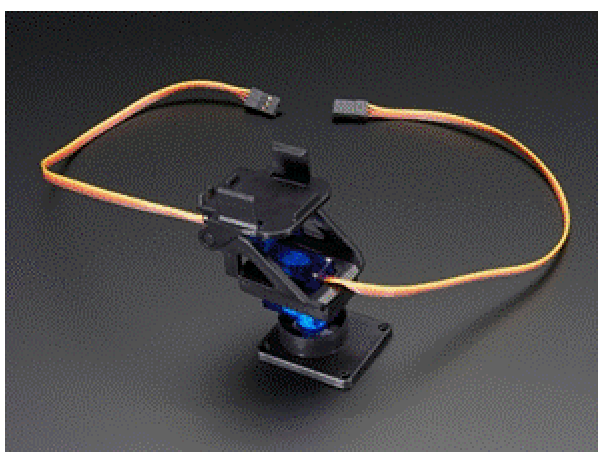

*Figure 26: GHH PT Pan/Tilt Camera Platform*

Reprinted with permission from Adafruit

**N-BK7 Bi-Concave Lens: KBC013**

In order to build a Galilean beam expander, a bi-concave negative lens shown in Figure 27 will be used to diverge the rays of the input laser light at an effective focal length of -6.3 mm showing it is a very powerful lens. This very short focal length helps tremendously with design specifications as the magnification of the system is the focal length ratio of the two lenses. Its design wavelength is 589 nm which is close enough to the input laser light, and its diameter is 6.35 mm which is plenty large for the input beam diameter of the LD of 2.5 mm.

*Figure 27: KBC013 Lens*

Reprinted with permission from Newport Corporation

**N-BK7 Plano-Convex Lens: KBC076**

This plano-convex lens shown in Figure 28 is a good candidate for the second lens as its plano-convex design helps minimize spherical aberrations. Its effective focal length is 25.4 mm which would yield an approximate magnification of 4x with the KBC013 lens which meets our design specification. Its design wavelength is the same as the first lens of 589 nm, and its diameter is 25.4 mm which is large enough to handle the largest possible output beam from the first lens.

*Figure 28: KBC076 Lens*

Reprinted with permission from Newport Corporation

**Diffraction Gratings: Any Frequency**

A diffraction grating with 100 lines per mm has an average spacing or order around 0.9 cm. To create unique patterns and show lights from gratings, multiple horizontal and vertical gratings of ranging frequencies will need to be tested. Additionally, masks such as slits, pinholes, and special symbols may be utilized to best fit an approved projection.

**Polarizer**

Given the decision to purchase 1064nm 50mW Laser Diode Module from CivilLaser for the laser rangefinder, a polarizer is needed to lower the output power of the system to ensure we meet our safety standard of 5 mW output. The only specifications needed to be achieved by the polarizer is to simply eliminate 45 mW of optical power and work with the 1064 nm output wavelength. By definition of a linear polarizer, both specifications are met by any legitimate working linear polarizer. With that established, the only things to look for when finding a polarizer is the size of the device and the cost. Our search found the AmazonBasics Circular Polarizer Camera Lens Filter - 52 mm. This unit is a polarizer large enough for our IR laser beam and has additionally layers of filters to improve performance. The cost of the polarizer is $11.49.

# 4 Related Standards and Realistic Design Constrains

This chapter will examine the standards and constraints that relate to the APES and its development. These topics are the guiding principles of the product's design and must be kept in mind when working on any aspect.

## 4.1 Standards

Every product needs to conform to the standards that has been set for similar systems. This is in part to ensure the safety of the product and to ensure the smooth transition from the design and prototyping phases to the manufacturing phases of the product's lifespan.

### 4.1.1 Laser Safety Standards and Classifications

The American National Standards Institute (ANSI) has developed four broad classifications of lasers based on their potential biological damage. The lasers will fall into these classifications based on parameters such as wavelength, average power, and exposure time. These parameters are used to develop new definitions which will govern how the laser is classified. The first definition is the Accessible Emission Limit (AEL) which is the product of the two other definitions, Maximum Exposure limit (MPE) and the area of Limiting aperture (LA). AEL is based on the power emission of the laser itself, while the MPE is based on time on biological tissue such as skin or eyes before immediate or long-term injuries.

Each laser class is based on thresholds of AEL from ANSI:

- Class 1 lasers cannot have accessible radiation in excess of Class 1 AEL for any exposure time within the maximum duration inherent to design or intended use. They are exempt from all beam-hazard control measures.
- Class 2 lasers have wavelengths between 400 nm to 700 nm, can only exceed Class 1 AEL for emission durations over 0.25 seconds and average radiant power of 1 mW or less.
- Class 3a lasers have output radiation between 1 and 5 times Class 1 AEL for wavelengths less than 400 nm or greater than 700 nm. They can have output radiation less than 5 times Class 2 AEL for wavelengths between 400 nm and 700 nm.
- Class 3b lasers cannot emit average power greater than 0.5 Watts for exposure time equal to or greater than 0.25 seconds between 180 nm and 400 nm or between 1400 nm and 1 mm. Wavelengths between 400 nm and 1400 nm exceeding class 3a AEL cannot emit average power greater than 0.5 W for equal to or greater than 0.25 seconds.
- Class 4 lasers exceed class 3b AEL.

The International Electrotechnical Commission (IEC) has developed their own classes based on AEL with the additional viewing conditions:

- Class 1 lasers are low risk and safe under its intended usage including the use of optical instruments for intrabeam viewing.
- Class 1M lasers have wavelengths between 302.5 nm and 4000 nm and are safe except when with optical aids. Optical aids that are within 10 cm from the output port of a diverging class 1 source are considered Class 1M.
- Class 2 lasers have wavelengths between 400 nm and 700 nm with powers up to 1 mW. If emissions are outside the wavelength region the exposure levels must be below Class 1 AEL. These lasers have minimal risk as they are visible and can naturally be avoided by blinking and evading.
- Class 2M have wavelengths between 400 nm and 700 nm and are hazard with optical aids. Emissions outside the wavelength region must be below Class 1M AEL.
- Class 3R lasers emit power between 1 and 5 mW with wavelengths between 302.5 nm and $10^6$ nm with potential hazard. The AEL is 5 times higher than class 2 AEL for visible light (400 nm to 700 nm), and 5 times higher than class 1 AEL when outside the wavelength region.
- Class 3B lasers emit power between 5 and 500 mW and are hazard with direct intrabeam viewing but are safe with diffuse reflections.
- Class 4 lasers emit power over 500 mW and are hazardous with intrabeam viewing and diffuse reflections for the eye. The lasers are capable of skin injuries and starting fires.

Table 9 is the overview of the classes of lasers according to the IEC. For each class it includes the type of lasers, how safe they are, their MPE, their hazardous areas, and a CW laser example.

*Table 9: Overview of Laser Safety Classes*

Reprinted with permission from Rockwell Laser Industries

| **Class** | **Type of lasers** | **Meaning** | **Relationship to MPE** | **Hazard Area** | **Typical AEL for CW Lasers** |
|---|---|---|---|---|---|
| Class 1 | Very low power lasers or encapsulated lasers | Safe | MPEs are not exceeded, even for long exposure duration (either 100 seconds or 30000 seconds), even with the use of optical instruments | No hazard area (NOHA) | 40 µW for blue |
| Class 1M | Very low power lasers; either collimated with large beam diameter or highly divergent | Safe for the naked eye, potentially hazardous when optical instruments** are used | MPEs are not exceeded for the naked eye, even for long exposure durations, but maybe exceeded with the use of optical instruments** | No hazard area for the naked eye, but hazard area for the use of optical instruments** (extended NOHA) | Same as Class 1, distinction with measurement requirements |
| Class 2 | Visible low power lasers | Safe for unintended exposure, prolonged staring should be avoided | Blink reflex limits exposure dura-tion to nominally 0.25 seconds. MPE for 0.25 seconds not exceeded, even with the use of optical instruments. | No hazard area when based on unintended exposure (0.25 seconds exposure duration) | 1 mW |
| Class 2M | Visible low power lasers; either collimated with large beam diameter or highly divergent | Same as Class 2, but potentially hazardous when optical instruments** are used | MPE for 0.25 seconds not exceeded for the naked eye, but maybe exceeded with the use of optical instruments** | No hazard area for the naked eye when based on accidental exposure (0.25 seconds exposure duration), but hazard area for the use of optical instruments** (extended NOHA) | Same as Class 2, distinction with measurement requirements |
| Class 3R | Low power lasers | Safe when handled carefully. Only small hazard potential for accidental exposure | MPE with naked eye and optical instruments may be exceeded up to 5 times | 5 times the limit of Class 1 in UV and IR, and 5 times the limit for Class 2 in visible, i.e. 5 mW | 5 times the limit of Class 1 in UV and IR, and 5 times the limit for Class 2 in visible, i.e. 5 mW |
| Class 3B | Medium power lasers | Hazardous when eye is exposed. Wear Eye Protection within NOHA. Usually no hazard to the skin. Diffuse reflections usually safe | Ocular MPE with naked eye and optical instruments may be exceeded more than 5 times. Skin MPE usually not exceeded. | Hazard area for the eye (NOHA), no hazard area for the skin | 500 mW |
| Class 4 | High power lasers | Hazardous to eye and skin, also diffuse reflection may be hazardous. Protect Eye and skin. Fire hazard. | Ocular and skin MPE exceeded, diffuse reflections exceed ocular MPE | Hazard area for the eye and skin, hazard area for diffuse reflections | No limit |

## 4.1.2 Laser Hazards

Severe and irreversible biological damage can happen from lasers if we are not careful enough. To know how best to design the lasers, it is important to know the hazards lasers pose on organic tissue, mainly the eyes and skin. We will examine the absorption spectra of various parts of the eyes and skin which in turn will aid us in our safety constraints. Safety constraints will be the largest of constraints on the design of the project as the autonomous laser will constantly move positions around the room and may come into contact with biological tissue. This guided laser will need to be designed to pose the most minimal risk of damage to any biological tissues including animals. It has been noted that human safety standards can be agreed upon as also pet safety standards for animals such as cats and dogs, and this means that the design constraints for human safety are the same for animal safety.

## 4.1.3 Absorption Spectra of Cornea, Lens, and Retina

The emission from a laser source can be thought of as many parallel lines known as plane waves that propagate orthogonally to the lines. The eye's function will naturally curve these plane waves so that they converge on a tight spot of the retina which will cause severe damage as all of the power of the wave is focused together. The damage done is not only a function of the power, but also wavelength, exposure time, and if it is a continuous or pulsed laser. These parameters will all need to be considered in laser design constraints.

While there are many eye components that contribute to the capability of the eye as shown in Figure 29, the cornea, lens, and retina can be considered the top three components that the eye needs the most and where ophthalmologists spend most of their efforts on.

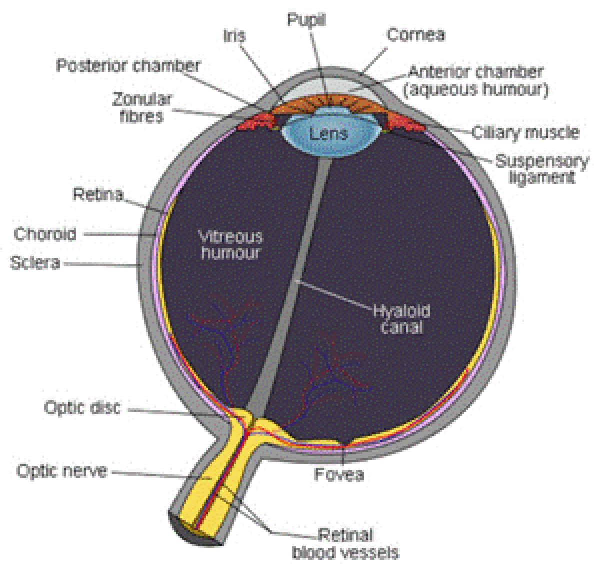


*Figure 29: Cut-away of Eye*

Reprinted with permission from Optique

The cornea is the first main optical element of the eye responsible for most of the converging power of the eye. Its absorption spectrum is shown in Figure 26. Wavelengths in the ultraviolet region (less than 400 nm) and in the far infrared region (above 800 nm) will cause the most severe damage. The spectrum shows that wavelengths near visible wavelengths (400-700 nm) have the lowest absorption around 5 to 10 percent and will typically cause damage that is not irreversible with low power. As the absorption increases and/or power, heating effects can occur which can destroy the cornea and will need surgery to replace it.

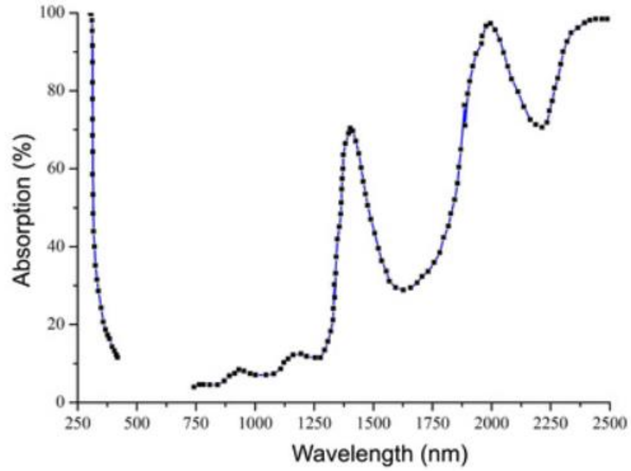


*Figure 30: Absorption Spectrum of Cornea*

Reprinted with permission from Optique

The lens of the eye is the next main optical component that serves the purpose of accommodation. It is a partially amorphous convex lens with muscles attached to it to change its shape hence change its optical power. This accommodation effect helps the eye focus near or far away objects onto the retina. Figure 31 shows its absorption spectrum. Similar to the cornea, for infrared and ultraviolet wavelengths pose serious risk of damage to the optical element. The damages in low powers can be reversible but will mainly cause permanent lesions.

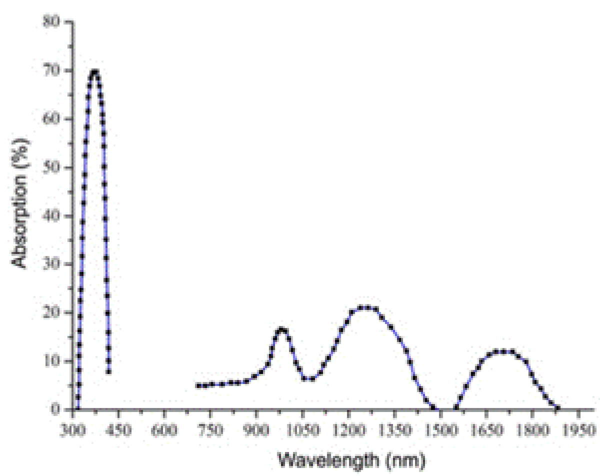


*Figure 31: Absorption Spectrum of Lens*

Reprinted with permission from Optique

The retina is the final main optical component of the eye that serves as the transducer; it converts light signals into chemical signals for the brain to interpret. The absorption and transmission spectra of the retina in Figure 33 can be explained by Figure 32. The retina has a few main components responsible for various tasks such as the photoreceptors which are the rod and cone cells at the back. These photoreceptors are the part of the retina that can convert light into signals, and it will send the signals up the series of components that will reach the brain. Since the rods and cones are at the back of the retina, the retina itself is mostly transparent to allow light to reach the photoreceptors.

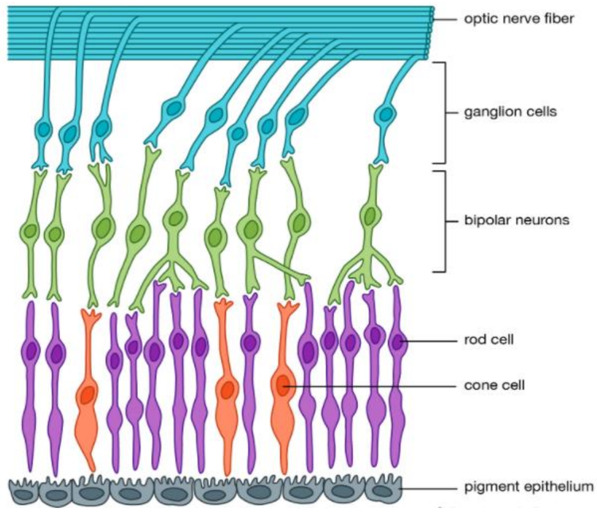


*Figure 32: Structure of Retina*

Reprinted with permission from Optique

Visible and infrared wavelengths are the most transmitted wavelengths in the retina according to Figure 33. This will make these wavelengths have the most associated risk contrary to the other optical elements (cornea and lens). The cornea and lens had risk that stemmed from its absorption percentage since their function is to transmit as much light as possible so as to not get heated and damaged. The retina has a different case where its risk stems from its transmission percentage since the oncoming laser light is being focused and will damage the sensitive rods and cones easily if the light reaches them. The absorption spectrum of the retina acts like a barrier against the light; the high absorptions will protect

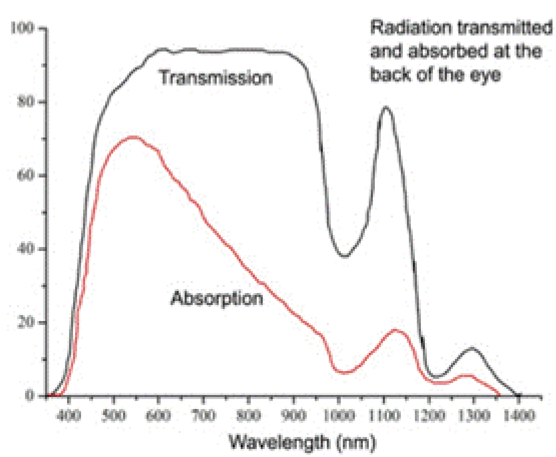


*Figure 33: Absorption and Transmission of Retina*

Reprinted with permission from Optique

the photosensitive cells at the back of the retina by lowering the light intensity before it reaches them.

### 4.1.4 SystemC® Standard for Software Design

IEEE 1666-2011 is the standard that defines SystemC. As described in the standard summary, SystemC is an ANSI standard class library of C++, used in the design of hardware and software systems. Specifically designed to for designers and architects that need a system with complexity to address its needs. This contrast with more traditional hardware languages that require much more design to accomplish the complex task that the SystemC library can. The APES uses an ATmega328p chip for its sensor readings and navigation systems, this chip is programmed using Arduino programming language that is similar in structure to the C++ language so this standard provides a guideline that guarantees we are implementing software in a trusted manner.

### 4.1.5 C Standard

The standard C language is described inside the IEC 9899 developed by the ISO, international organization for Standardization. The standard covers the interpretation of programs written in C and specifies the form in which the programs should resemble. It specifies a crucial aspect of the C language to promote a common representation of C. Specifically things such as syntax and constraints of the language, the semantic rules for intepretng the programs written in C, representation of input data that is processed by C programs, and the restrictions and limits imposed by a conforming of C. We include a description of the language as a basis to demonstrate why the use of the arduino language allows for a better control of the microcontroller when compared to traditional hardware design languages. C and its derivatives are light weight in comparison to other programming languages allowing it to replicate hardware language behavior and more complex task without as much overhead. This is crucial for our project and most microprocessor designs due to the limited memory and storage available to microprocessor. While this has changed due to more complex microprocessors becoming increasingly smaller, for our project the lightweight and cheaper ATmega328 benefits from the limited size of the C like languages. Furthermore, the ability to use custom defined data structures on a lightweight language allows for an exponential increase in complex capability while not sacrificing cost and forcing us to use a more expensive processor for simpler task. Finally, C is one of the most commonly used languages in which provides decades of material to act as references. This limits the cost of research necessary to use the language in our programs.

## 4.1.6 Arduino Language Reference

The Arduino Language reference while not an official standard created by any recognized committee, still acts as a reference for the language that is used to drive our arduino chip. The importance of the standard is due to ATmega328 being the chip we are using to drive multiple subsystems in the APES. ATmega328 actually uses its own language that while similar is technically different than C, some refer to it as a library but in official practice the Arduino programming language is its own standalone language. Included in the document is list of functions that included with the language using only the standard library. Important to the language is functions for the reading of inputs and outputs via digitalRead() and digitWrite functions, this allows for reading of inputs and outputs to and from the chip's pins as a data type in the software without the need to worry about any specific identification of each individual pin.

This matters to the APES because it will be used in our system by the ATmega328, knowledge of C does not transfer to knowledge of the APL. For example, the APL has many functions regarding input and output to the pins on the microcontroller that are not easily transmitted to the C/C++ language, allowing a further streamlining from hardware languages. Our project will utilize multiple sensors the ability to treat those inputs as Boolean values in an algorithm will allow for complex observation of reality that APES require to function. Another unique aspect of the ALR is functions explicitly related to time included in the base language. Due to the nature of micro controllers being used in many devices that interface with the physical world constantly, time becomes something that is relevant to the operation of the project. Our project uses timers to determine the distance the system has moved during navigation so the ability to tell how much time has passed during the execution of one part of the algorithm to another allows us to tweak the operation in an intuitive way and have our system naturally interface with the passage of time during operation. Crucial to the navigation of time is the use of interrupts functions attatchInterrupt() and detatchInterrupt(), the system will be able to detect disturbances during navigation and to do so will require the use of interrupts to make sure the system does not attempt to operate in an unintended state. The final crucial defined functions of the base ALR is the serial communications functions. This section is actually over a dozen functions that cover the communication of pins 0 and 1 with an outside computer. Our system will use these pins to communicate with the RP3B to facilitate proper motion tracking. Using the official reference guarantees our product meets industry standard regarding the use of Adruino made chips like the ATmega328.

## 4.1.7 PEP 8 – Style Guide for Python Code

PEP 8 acts as the official standard and style guide for the python language. Developed by The Python Foundation, PEP 8 describes itself as" giving the coding conventions for the python code compromising the standard library in the main

Python distribution." Specifically, the guide serves to add a level of consistency when coding inside the python language. As stated in the document, code is more often read than written and thus readability counts. However, the style guide also puts functionality over aesthetic by cautioning users against adhering strictly to the guide if it makes the code unreadable or incompatible with code inside a project. Included in the standard is a section describing the layout of code written in Python covering specific indentation practices that allow for readability and advising against tabulation. Line length of 79 character is expected except in the case of comments which are expected to be 72. This standard is important due to the use of the Raspberry Pi 3B as the microprocessor used for the APES system. Raspberry pi's can use many different languages as due to their computational complexity however the use of Python as a simple to use language makes it one of the most used languages. More specifically the Open CV library being used for project is written in Python. By following the practices laid out in the standard we allow any troubleshooting and testing of the software written in Python to be streamlined. Furthermore, bugs can be more readily be identified and code reviewed much more efficiently. All these features will allow us to same time while designing the software and therefore resources that can be spent on other aspects of the project.

## 4.1.8 Pyhon Language Reference

The Python Language reference is developed by The Python Software Foundation as dictionary that describes the syntax and core semantics of the language. The document goes over the various implementations of Python that have developed while also making clear the common notation of Python. The document provides lexicological analysis of the structure of the code as interpreted by the parser. This includes logical line, physical lines, comments, the joining of line and indentation. [2.1] Most importantly the document covers the data models supported in native Python and their implementation. Python is capable of implementing objects of data that can store than own data values but contain methods that they can use to act upon themselves and other objects. This is crucial due to the use of various forms of inputs being transmitted by the camera inside the system. Reading frames in and training the algorithm is streamlined by having all the data and functionality of the program stored in the same place.

## 4.1.9 Software Testing Standard

This standard is described in the ISO/IEC/IEEE 29119, and goes over a combination of testing standards that used to allow for an "internationally-agreed upon set of standards for software testing." These standards were designed with the intention of any organization being able to implement them when performing their own software testing. Using this standard as a guideline allows for the proper implementation of testing processes and ensures that the software meets the level of functionality and the goals of the project. The standard itself contains four parts which we will briefly go over and relate to our project.

Part 1 is described to facilitate the rest of the standard by providing the vocabulary that is used as the basis of the standard and provides a description of concepts of software testing and ways to apply the definitions and concepts to the testing of software,

The purpose of the Part is to actually define the “test processes that can be used to govern, manage, and implement software testing”. The test process is broken down into three levels: the organizational lever, the test management level, and the dynamic testing level. The organization level is where the creation of testing procedures at the organizational level, agreed upon by the managers of the organization. The organizational level is more about creating a rubric of policy and strategy that the organization can use while testing the software.

The test management level is primarily concerned with the actual testing of various subsystems and is further broken up into three smaller systems. These test planning, test monitoring and control, and the completion of the test. For the planning of the test the standard lays out different plans for testing the software including the project test plans and test plans at various levels of the project. Once planning is complete this is where we make observations of the test to determine how well our system responds and what adjustments need to be made. Once testing is complete, we can this level provides feedback to the organizational level to facilitate an improvement of testing policy.

The dynamic testing level acts a check on the completed test process and is where we make sure the environment in which we test the software is adequate and actually perform the test on the software. Incidents are reported and feedback is sent back up the chain to the organizational level to further make sure testing is done properly.

These testing processes guarantee our software is properly implemented and that any error have a proper reaction from the group to be dealt with quickly. Which saves us time and resources.

## 4.2 Realistic Design Constraints

As the potential project thoughts were being formed within our group, we all had to consider the various constraints that essentially limited our discussed ideas. The list of constraints of their respective categories have molded the shape of this project. These constraints are to set limits, so the project’s design is realistic in regard to the amount of knowledge, time, and money our group has. While some constraint categories are more prominent than others, they will determine the requirement specifications and provide reasoning for the design. It is very possible that the constraints listed will become too overbearing as the project is built and start to break down the number of features or capabilities this project has. Design constraints are important to every project and are essential to know about before starting any potential designs. The following categories are the constraints of the project and how the respective subject affects the end design:

- Economic and time constraints
- Environmental, social, and political constraints
- Ethical, health, and safety constraints
- Manufacturability and sustainability constraints

## 4.2.1 Economic and Time Constraints

The initial budget of the project was to be roughly $400 to $500 divided evenly among the group. This severely hinders what components need to be bought especially for laser diodes since their cost can vary greatly with wavelength. Additionally, LED and photodetector's quality and quantity are hindered by this amount which can in turn affect the accuracy of proximity measurements.

This project has a weakness in its proximity measurements as the LEDs will not be able to accurately signal to the photodetectors when an object is within a few millimeters of the device. While it is possible to solve this problem with a little more ingenuity and money, it would be much simpler for the project to ignore this and not buy additional elements for such a small constraint.

Computer vision and camera type is hindered greatly by this budget since there are many software's that are easily capable of tracking but are not entirely available to a team like us. Camera resolution is a parameter that can affect the accuracy of computer vision and is hindered by our budget. The camera choice will need to be low-end despite having the resolution for high accuracy tracking and *color* vision.

The robotics of the device poses a burden on the project that affects its specifications such as speed, rotation, and maneuverability. The servos and motors of the device will need to be as low end as possible as to not subtract significant amounts from the core features. The speed and terrain-accessibility of the device is not of priority and will need not to be given much design detail.

The time constraint takes into account the various aspects of the project and roughly how long it will take to prototype, implement, test, etc. these features. This is perhaps the most ambiguous constraint but also the most demanding. Time constraints will usually be the reason why a feature was deleted or changed in the project. We only have roughly one semester to plan out the aspects of the project, and another semester to get the parts together to work on and to build up the project. In that time, we will need accurate tracking of the laser, and distance triangulation. The project Milestones section will aid us to deal with this constraint.

## 4.2.2 Environmental, Social, and Political Constraints

For our project to meet environmental, social, and political constraints it will need to use materials that comply with the authorities. Most of the materials and components that will be used, are to be purchased through vendors who most likely are already using materials that complies with regulations for the environment and government policies. This is important as if the product was to be disassembled, then there will pose no environmental harm. An instance of this can be the battery supply of the project. There are batteries available that need special care or even outlawed, so the power supply/batteries we use will have been regulated.

Social and political constraints involve trademarks and patents. There are many autonomous laser pet toys on the market that make use of a tracking laser to distract cats. Some of them can be stationary or can move, can rotate 360 degrees horizontally or less, and can use different modes of laser patterns. Our project will need to be different from all of these trademarks of the various cat toys and be unique in its own way as to avoid lawsuits. We have added features such as telescopic lenses and diffraction grating to give our project uniqueness and have taken aspects of different designs such as wheels and motion sensing to combine them as our own invention.

## 4.2.3 Ethical, Health, and Safety Constraints

The ethical, health and safety constraints mainly stems from the laser usage. The laser standards set by ANSI and the IEC will need to be adhered to so there is not any damage to biological tissues of humans or pets. According to Table 1, both of our laser diodes will not be able to reach Class 3 and will be most likely in Class 2 or Class 2M. Class 2 lasers are low power and are safe to be around, but should not be exposed to the eye directly for a lengthy amount of time (greater than 0.25 seconds). Class 2M lasers can get hazardous when there are optical elements in the beam path such as our projector laser with the telescopic lenses system. If the Class 2 lasers are too unsafe to be around, Class 1 lasers are very acceptable since they have minimal hazards and can be exposed to the human's face. However, Class 1M lasers still pose danger to the eye even with low power. The MPE is the primary variable that is considered for Class M and changes its hazard status. To avoid the danger, this laser light tracking may need additional programming to not move towards a cat's or human's face. Other failsafe's will be considered if the laser light proves too dangerous.

In the Laser Hazards section, the most susceptible biological tissue was examined to see how it fares against the spectrum of wavelengths. Skin tissue is not examined since it cannot possibly be hurt by laser classes lower than 3, which are classes 1 or 2 that we will use. The eye can still be hurt by laser Classes as low as 1M, so it is important to know what the most dangerous wavelengths of the spectrum are.

Three main components of the eye and their absorption spectra were measured in the Laser Hazards section and by analyzing and combining their information, the safest laser wavelengths can be determined. Both the cornea and lens had little to no absorption (e.g., capability of taking damage) in the visible wavelength region so this helps the cat to see the light easily and be distracted on and helps humans have blink aversion as to not be damaged by the laser light. However, our distance measuring laser will need to be in the IR range for easier measurements, but it has significant absorption in the cornea and lens of the eye. This laser light is invisible and can pose a serious risk to the cat even though it is stationary and very low to the ground. There will need to be countermeasures for this particular light source.

The retina is the last optical component of the eye to be considered and its transmission spectrum which is responsible for its capability of taking damage is extremely high in visible and infrared wavelengths. Any laser light that is not extremely small in radiant power that manages to reach the retina will most likely burn it. However, the absorption of the retina (e.g., protection against light) shows that it peaks around 550 nm which will be the safest visible light to the retina. Our tracking laser will most likely be around this wavelength. Additionally, the transmission and absorption of the retina dip significantly around 1000 nm in the IR wavelengths. This will most likely be the wavelength of our IR distance laser.

Although we want to have a very visible and shining laser beam, there is such a thing as “too bright.” When the laser increases its power, the luminosity of the beam gets very bright and can start to strain the eye. The eye can be strained even when not looking directly at the beam. This is serious concern of our project since light projections such as screens and displays also consider their average brightness or luminosity. In our design, we must make sure that the brightness and in turn the optical power in mW is at an acceptable power that does not strain the human or cat’s eyes and can be looked at with ease.

### 4.2.4 Manufacturability and Sustainability Constraints

Manufacturability and sustainability deals with the complexity of the device and its components and how intricate it is, which in turn affects the reproducibility and lifetime of the device. Judging that the autonomous pet toys on the market are typically in the 20 to 40 dollar range, it means that the complexity of its design is very basic and ours is no different. This device could easily be assembled, and mass produced if needed to. The device is designed so none of the components are exposed to the outside as protect the device and lengthen its sustainability. The device will need to comply with power standards and operate in a way so it will not short any of its components, the average battery lifetime will be determined based on these constraints.

Since our project is purely autonomous, many of the functionalities rely on algorithms which are input-based codes that react to stimuli. For instance, if a wall which is a stimulus gets too close to our project, the IR sensors will give feedback on the stimulus (low light) and send that data to the program. The program knows that when that particular IR sensor has too low light at a threshold, it needs to react by sending a signal to the propulsion system telling the system it needs to move the opposite direction.

Autonomy of our project means it relies on these algorithms to guide it for its intended objectives and goals. The constraint of this condition is the complexity of algorithms. In our limited knowledge and members, it may prove difficult to code algorithms that has too many situations and possibilities it can do. Our algorithms created will need to be simple and use basic logic to operate the APES.

# 5 Hardware Design Details

This chapter will discuss the designed implementation of the physical components making up the product. Each primary and secondary subsystem design will be explored.

## 5.1 Initial Design Diagrams

The initial ideas and designs for this product stemmed from the first ‘Divide and Conquer’ document. This document put forth the intended purposes and operation of the toy as well as the initial design characteristics before the majority of the design research was performed. Figure 34 shows the operation flowchart that was developed for the ‘Divide and Conquer’ document.

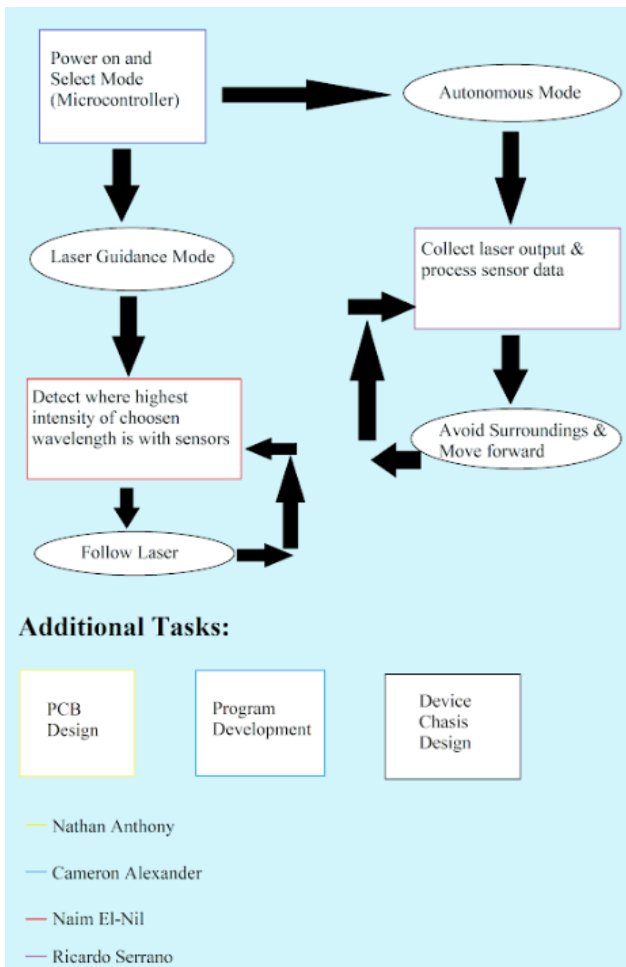


*Figure 34: Divide and Conquer Operational Flowchart*

Figure 35 was also developed for the ‘Divide and Conquer’ document and pertains to the initial software flow of the toy.

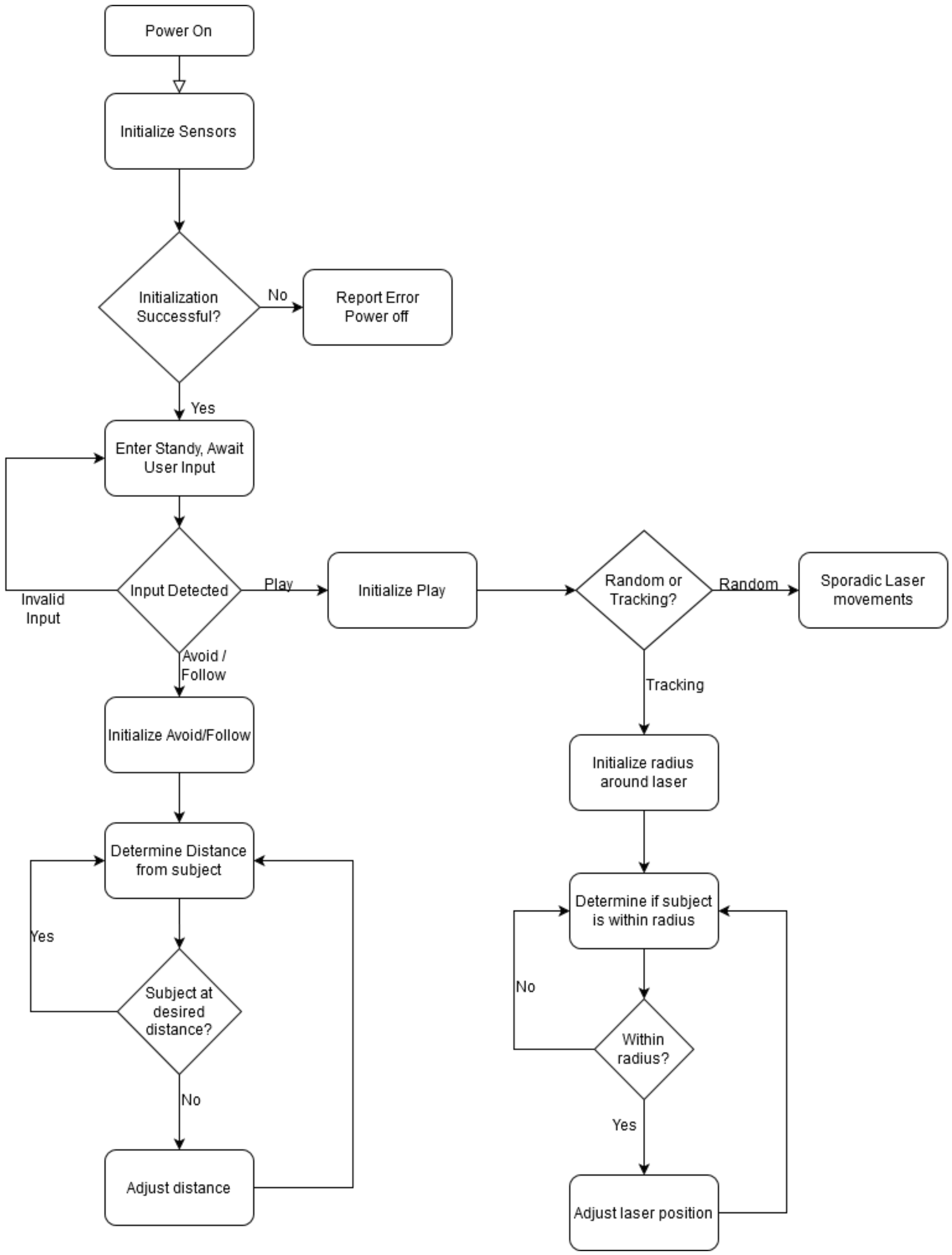


*Figure 35: Divide and Conquer Software Flow*

Once some initial research was performed, a subsystem and component organization chart were developed to help visualize how each component would assist in the operation of the toy. This is shown in Figure 36.

Once an idea of how everything would work together was developed, next came the actual physical design of the toy and how to effectively place parts so that they operate as intended. For this, Figure 37 was created.

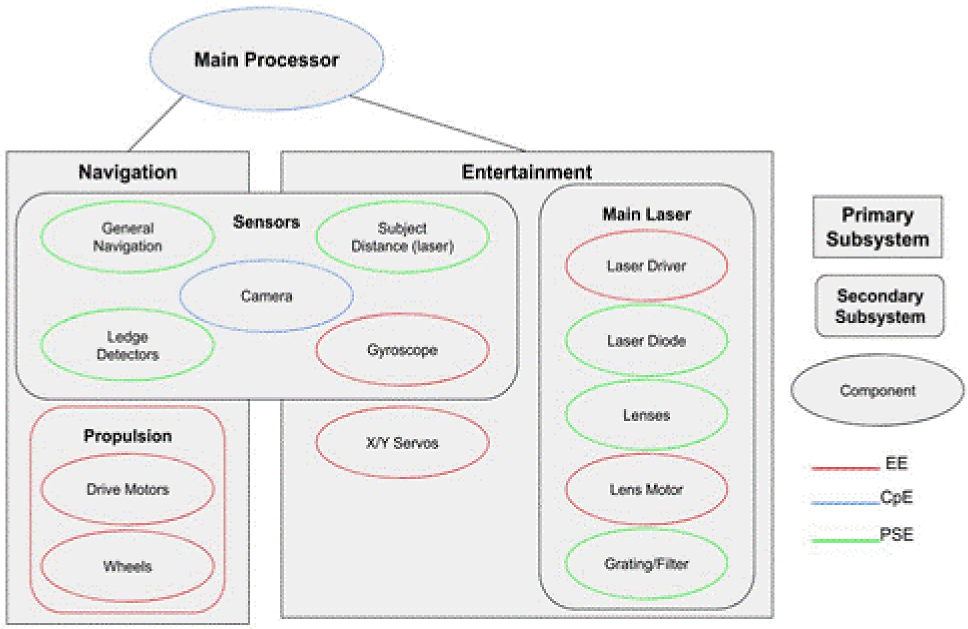


*Figure 36: Subsystem and Component Organization*

These figures were instrumental in the development of our product; however, they are only a starting point. Throughout the design and testing process there will be unforeseen challenges that force the vision to change and adapt. Everything seen in the above figures are subject to change whether it be slight pivots or complete overhauls. Despite these looming changes, these figures are of the utmost importance. They guide all the research, design decisions, component selections, work distribution, and a number of other factors. It would be nearly impossible to begin a project as extensive as this without these kinds of diagrams and it would certainly be impossible to finish.

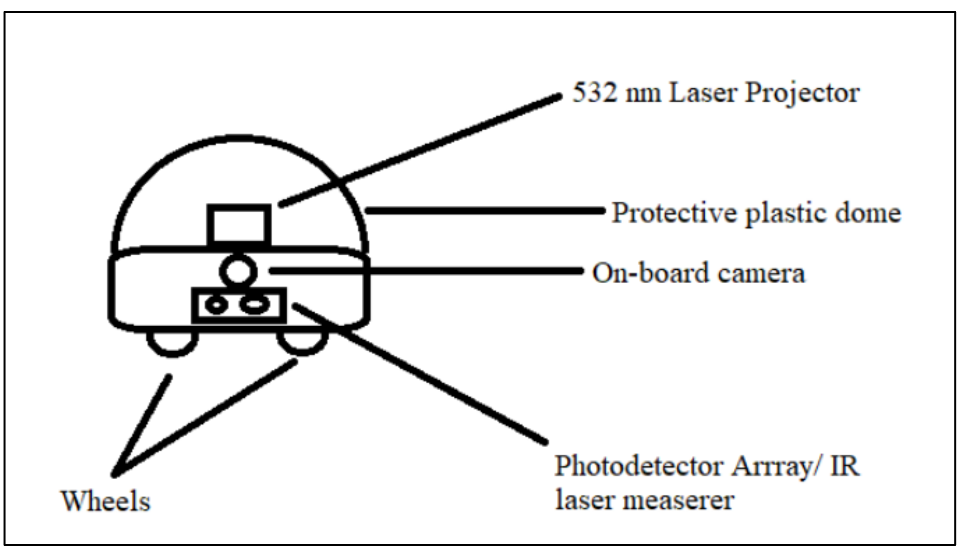


*Figure 37: Initial Physical Design*

# 5.2 Subsystem 1 - Navigation

As shown in Figure 32, the APES can be divided into two primary subsystems: Navigation and Entertainment. This section will be discussing the Navigation subsystems and the secondary subsystems within it. These include the main propulsion system of the toy as well as the sensors related to this task.

## 5.2.1 Propulsion

The propulsion system has the ever-important task of providing the locomotion for the toy. This system is one of the ways that the APES sets itself apart from its market competitors. The ability to move itself freely around an environment opens many opportunities for dynamic play which is vital to keep a cat interested. This is something that simply is not found in the various stationary automatic laser pointers currently available. The movement of the laser pointers on today's market claims to be random and sporadic but upon a closer look, the lasers only ever move along one set path which is very easily predicted. Whether that be a circle around the device or an ellipse away from the toy, it will get stale very quickly unless someone actively moves the toy to different locations. The propulsion system on the APES allows for a truly hands-off dynamic play experience by repositioning itself autonomously before resuming play with the cat.

The system will be generally arranged as shown in Figure 38. Note that this diagram is not drawn to scale.

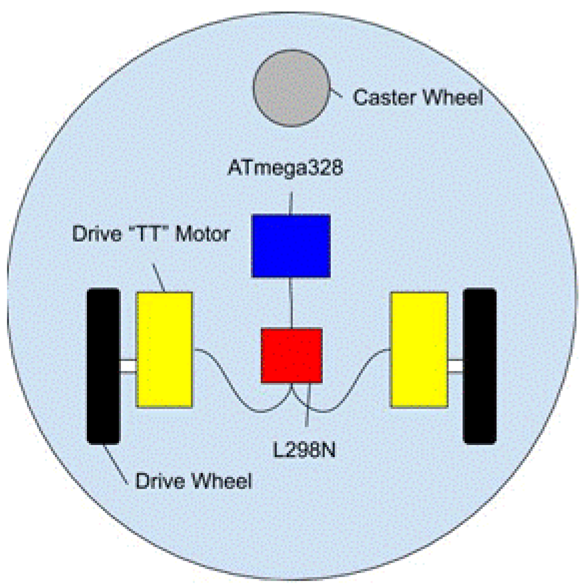


*Figure 38: Top-down View of the Propulsion System*

As shown in Figure 38, the APES relies on a three-wheeled design to maintain balance and maneuverability with two independent drive wheels at the rear and a single, free-spinning caster wheel at the front. This arrangement allows for the most maneuverability with minimal complexity. The toy will be capable of zero-radius turns to successfully navigate any obstacle.

It can be seen that the drive motors are not connected directly to the Arduino microcontroller. Instead, they are plugged into a motor driver which is then connected to the Arduino. This is because an Arduino is not equipped to safely drive motors without external assistance. The motors can generate copious amounts of return voltage and noise which will seriously damage the controller; thus, the motor driver protects the controller.

The motors are controlled via Pulse Width Modulation (PWM). This allows for the motors to be run at different speeds and in different directions via the change in duty cycle of the digital signal being output from the Arduino.

### 5.2.2 Sensors

**Laser Rangefinder**

Our design features a fully operational laser rangefinder in the front facing direction. The rangefinder is designed to aid the camera that will be mounted above the rangefinder to aid in the camera's distance measurements. These measurements are used to get an accurate navigation system that does not have to rely on estimated calculations from the images gathered by the camera.

The design of the system is shown in Figure 39 and features an infrared 1064 nm laser diode for the light output, two convex lenses and a photodetector. All laser output from any laser diode is diverging and must be focused by a lens with positive optical power to form a usable beam. Once the beam is focused by a lens, the laser is shined onto any surface directly in front of the apparatus. The beam will then reflect off the surface it hits in one of two methods: Specular reflection or Lambertian reflection. Specular reflection assumes a perfect retro-reflection off a surface with no imperfections and minimal power loss. While this might be a viable method to consider in a laboratory, specular reflection rarely occurs in real life even with the most ideal materials available. Lambertian return is the assumption that all surfaces will diffusely reflect any light that hits it much like a matte material. In the instance of a standard living room, most materials are rather rough in texture when only several inches off the floor. The assumption of Lambertian return is that the reflected beam is reflected in multiple directions with varying power and is much more realistic in our circumstances. Once the beam reflects, there is a highly likely chance that the beam will return to the general area where it left the lens. This is why the second convex lens and photodiode are placed right next to the laser diode and its respective convex lens. The convex lens will take the incoming reflected beam and focus it onto the surface of the photodiode. Photodiodes take light and convert them into electrical signals. These generated electrical signals will be amplified by a circuit and sent to the device's microprocessor where it will be interpreted into usable time data. The computer will record the time it takes from turning on the laser diode to when the photodiode receives the beam on its surface.

This delay in time is then used to calculate the distance the beam has traveled since it was launched. Calculating the distance traveled is achieved by multiplying the time delay by the speed of light (299,792,458 m/s) and then halving this product to account for the fact that the laser beam has traveled the distance twice since it was launched.

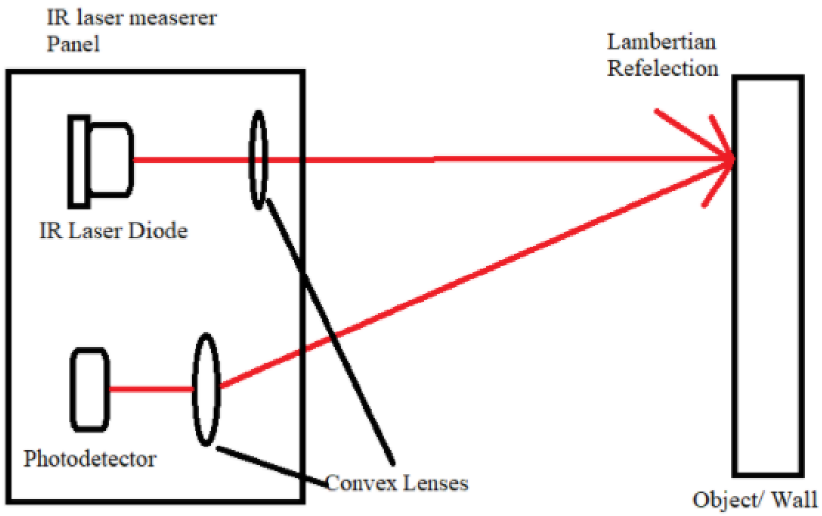


*Figure 39: Laser Rangefinder Layout*

Our calculations can be made even more accurate by simply adding another photodiode, laser diode and convex lens in a different area from the existing one. The additional photodiode will allow us to have another set of data to allow us to use a different method of measurement: triangulation.

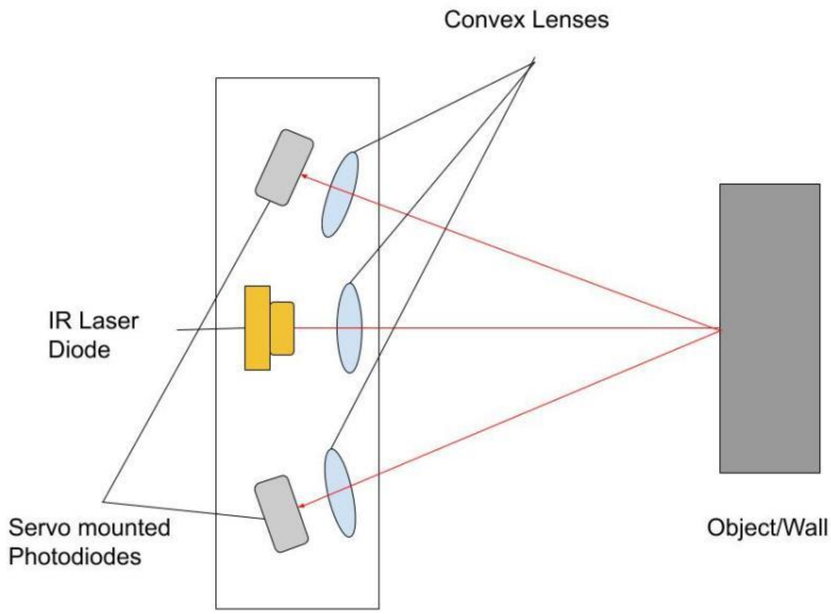


*Figure 40: Laser Rangefinder Arrangement Utilizing Triangulation*

The final design of the laser rangefinder is shown in Figure 40. This design utilizes two laser diodes and photodiodes in order to use triangulation as a method of measuring distance. Since measurement via time of flight is incredibly fast, it would require extremely fast computer processing. This time-of-flight measurement was cut as the required computational speed and power would be far too expensive for any average consumer to afford.

Trigonometry distance measurements requires only the distance between the two laser diodes and the two angles at which the laser diodes give the highest reading on their respective photodiodes. The distance between the two diodes is always fixed so there is no need to calculate it. Angles of the laser diodes are acquired from operating servos attached to the diodes at small increments and comparing the voltage generated by the photodiode. The angle at which the most voltage is generated by the photodiodes correspond to the angles needed to find the distance of the object in front of the arrangement. Using the following formula, we can calculate the distance from the device to the object that is in front of it:

$$d = l\,(\frac{\sin\alpha\sin\beta}{\sin\alpha+\beta})$$

*Figure 41: Triangulation distance formula*

where d is the distance from the object to the device, l is the distance between the photodiodes, α is the angle acquired by one pair of diodes and β is the angle measured by the other diode pair.

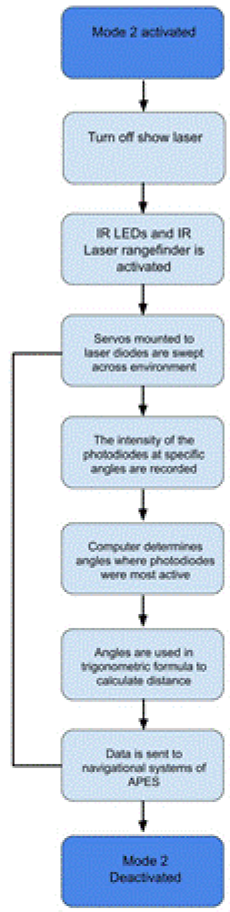


*Figure 42: Laser Rangefinder Operation Flow Chart*

Once triangulation was determined to be the method of operation for the laser rangefinder, Figure 42 was developed. This figure shows the order in which the system operates the rangefinder once mode 2 is activated. The rangefinder is deactivated once the device exits mode 2.

**LED Based Sensors**

Besides the front of the device, our design must consider obstacles around it in order to navigate a complex environment. Our laser rangefinder can only aid in navigation in front of the device to move forward but cannot aid in any other direction. Additionally, the APES may only move forward but still must be able to detect any obstacles behind it and to its sides. Unlike navigation in the front, there is no need to identify what the obstacle is. Only the relative distance from the device to the obstacle is required. We can deduce that using multiple laser rangefinders for this purpose is unnecessary and expensive. A simple alternative to using lasers would be using LEDs and complimentary photodiodes. The LEDs emit diverging light at a specific angle that only needs to be measured for its intensity rather than a time delay. A photodiode can be placed next to a LED and can measure the reflected return. When the photodiode reads an intensity like that of the max LED output, the microprocessor can process this data to avoid obstacles surrounding it on its sides and back. Multiple LED and photodiode pairs are placed around the device to help with navigation as more points of reference allow for higher accuracy. The wavelength of emitted light is chosen to be infrared to not bother any cats or humans. Specific photodiodes for these sensors are only sensitive to the LED wavelength which is different from the rangefinder's wavelength so there is no possible interference from one navigational unit to another.

APES will utilize four pairs of IR LEDs and photodiodes operating at 850 nm wavelength. The wavelength chosen is far enough from the front facing rangefinder's laser of 1064 nm to not interfere with the LEDs photodiode. Additionally, the selected photodiode for the LED has its highest responsivity to this wavelength. Each pair will contain one 850 nm LED and a complimentary photodiode on a driver circuit board. This board will power on both devices and read the output signal of the photodiode. Together, the assembled pair unit will have the standard positive and negative pins along with a third pin for the signal generated by the photodiode. The signal pin will be connected to the APES microprocessor for data analysis.

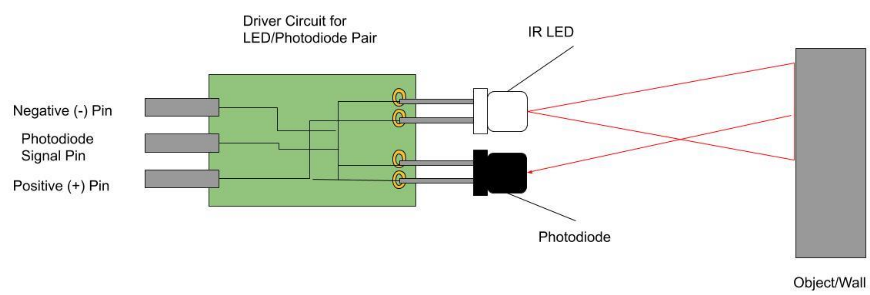


*Figure 43: IR LED/Photodiode Sensor Pair Layout*

Our four device pairs are strategically placed on the APES device for the best possible navigation results. The very front of APES is covered by the rangefinder and the camera so, it would be best to place the sensors outside of the camera's point-of-view. It is also important to note that APES does not travel straight backwards in any circumstance and only goes in a straight path. This tells us that no sensors are required for the back and direct sides of our device. With this in mind, we decided to take two pairs for each side angled toward the front of the device.

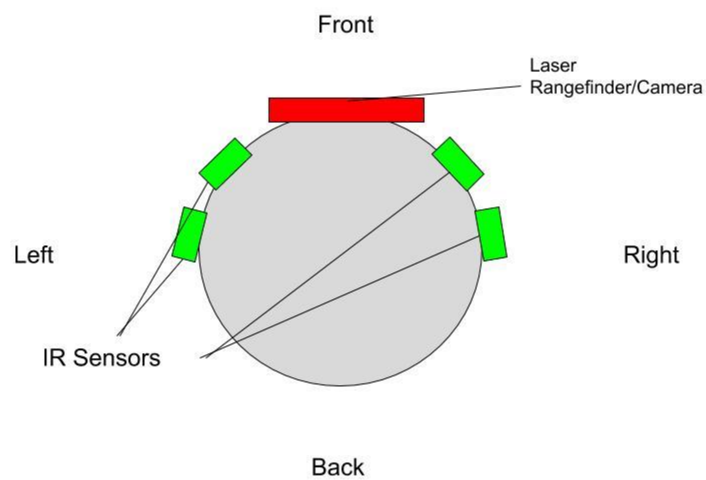


*Figure 44: APES Navigational Sensor Layout*

# 5.3 Subsystem 2 - Entertainment

The entertainment subsystem includes the main show laser, the accompanying sensors, and the servos that will move all of it.

## 5.3.1 Show Laser

The design for the laser pointer is shown in Figure 45. It features 4 main components: A 532 nm laser diode, an adjustable telescopic lens system, a mirror, and a diffraction grating or filter. A wavelength of 532 nm corresponds to a color output of green to human and cat eyes. This laser diode will have a max output of 1 mW to account for the eye safety of cats and humans near the device during operation. Since the light output of laser diodes are diverging, it will need to be focused by a convex lens. The first lens in the adjustable telescopic system accounts for this divergence issue and is the reason why the first lens cannot be adjusted. Our second lens in the system is designed to be adjustable via a motor in the axis of the laser beam. This second lens can be used to shrink the laser beam or make it larger through lens magnification. Once the beam passes through both lenses, it will be converging or diverging rather than being a straight collimated beam. To collimate the beam, a mirror is placed in the beam path at a 45° angle. This collimates the beam in a straight direction rather than having it diverge or converge through the rest of the system. The collimated beam may hit an optional diffraction grating or filter. These materials will alter the shape of the beam once it leaves the system into the environment.

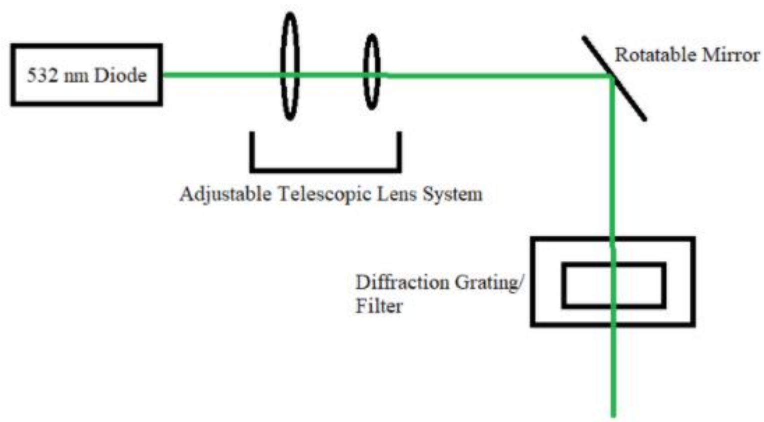


*Figure 45: Laser Pointer Layout*

The diagram below is inside the show laser tube where all the components for the show laser (laser diode, telescopic lens system, and diffraction gratings) are setup. This is essentially the housing and is connected to the servos mount which moves angles it vertically. The laser diode's beam has to be pass through the first lens of the lens system, and both the LD and collimating lens is stationary. The output lens moves to its variable positions to change its magnification on the translation area, which has a motor attached to it. After the beam passes the lens system, it reaches the grating wheel which has a closer view shown in Figure 46.

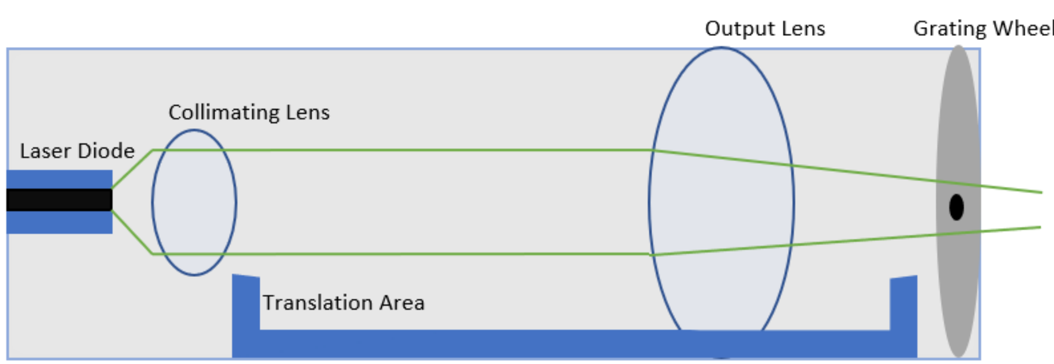


*Figure 46: Show Laser Tube*

The grating wheel hold all of the diffraction gratings we intend to use and is also connected to a motor. The motor rotates the position of the wheel, so the beam passes through only one grating at a time. Figure 47 shows some example gratings we intend to use normal shape grating is an open space that does not alter the beam shape, diffraction grating 1 is a linear grating, diffraction grating 2 is a double axis grating, and the special grating 1 is one of the special gratings we may implement. The number of gratings is for example and do not represent how many we intend to use, and additionally the grating sizes need to all be large enough so the beam may pass through it.

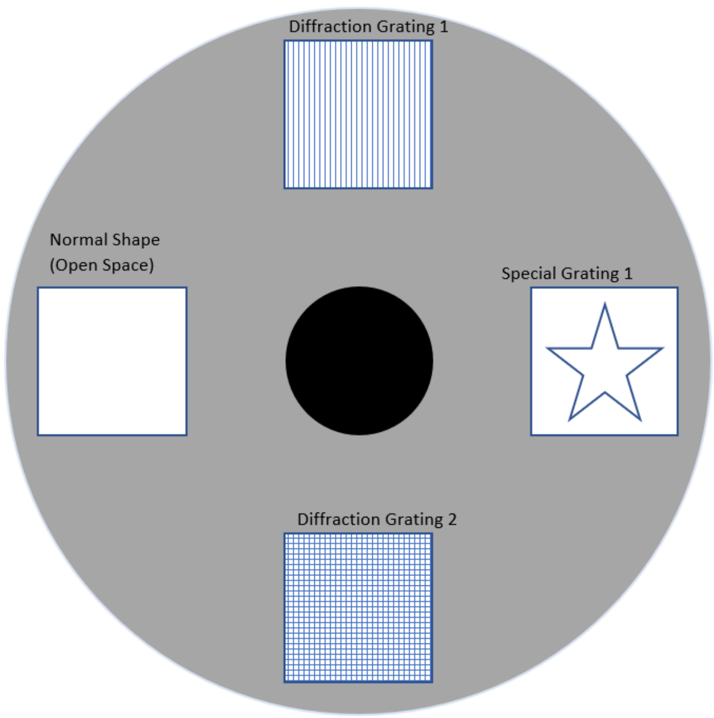


*Figure 47: Grating Wheel*

## 5.3.2 Show Laser Modes of Operation

The APES project will operate under pure autonomy and will change its magnification and output shapes under a time condition. Every ten seconds (or longer if needed), a random magnification and a random output shape will be switched to, but given that the total combinations amount is the various magnifications (at least five) multiplied by the amount of diffraction patterns (at least five) it will be unlikely for every combination to be selected in a reasonable amount of time.

To go through every selection in a reasonable amount of time, the algorithm will do random sampling without replacement. The included schematic below gives a general idea of what the algorithm will do, but the number of patterns (in this instance uses six but will be more) and their types in the schematic are for example. To start, the first block indicates that the first mode starts at a normal output shape with 1x magnification because it is surrounded in a red outline, and all other possible modes are available which are the five other green blocks. After ten seconds, another new mode must be picked randomly so it leaves the initial mode and goes to the dot pattern with 3x magnification. This is the second mode that is currently active as shown in the second block, and the first mode has been removed (shown to be whited out) which is the principle of sampling without replacement. After another ten seconds, the third new mode must be picked. There are only four choices this time as the normal shape with 1x magnification mode has been removed for the time being. The star shape with 1x magnification was randomly selected as the third new mode as shown in the third block. The dot pattern with 3x magnification mode is to be removed and cannot be picked for the next mode. As time goes on, all of the modes will have been removed so there is one mode active and the rest have been whited out. This means the loop has been completed and all of the modes can be added back to the sample size and be a

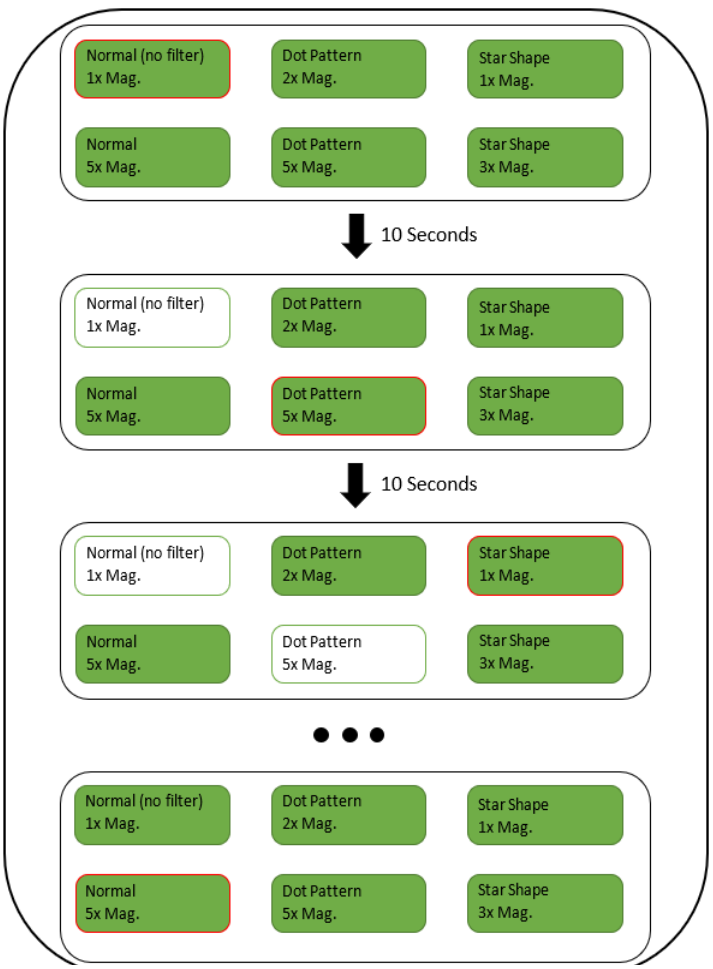


*Figure 48: Show Laser Algorithm*

mode that can be chosen. This is shown in the last block where all of the modes have been filled in, and the first new mode for the second loop is the normal shape

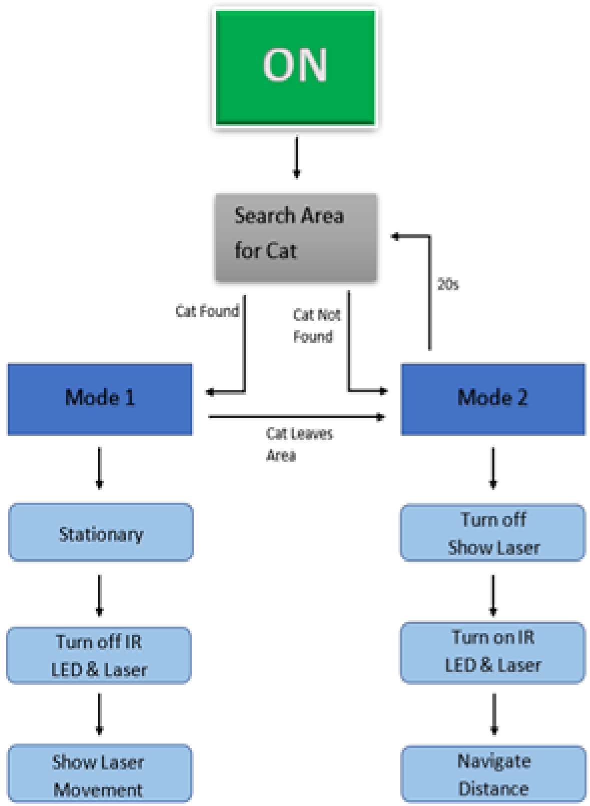


*Figure 49: Initial Startup*

with 5x magnification mode. This schematic was made to show how the lens system and diffraction gratings will be implemented autonomously.
The schematic above is what the APES project will follow on its initial activation. This schematic provides the sequence of what will need to happen for the final demo. On activation, the camera will be the only component active during the "Search Area for Cat" mode and it will scan the immediate area which is what is in front of the camera at the time. If the cat was not identified by the camera, it will go into mode 2.

Mode 2 is the navigation mode where its steps are as follows: turn off the show laser (if it was on), turn on the IR sensors (laser diodes, LEDs, and photodiodes), and lastly start moving. The algorithm for its movement will be explained at a later section with its own block diagram. During mode 2, the APES will move around with its wheels and motors and will avoid any front facing obstacles with its sensing technology. After a set time limit (roughly 20 seconds), the APES will have moved to a different location and now it can move back to the search mode and look for the cat. If the cat was not found or identified, it will need to start over again and move back to mode 2. If the cat is found, it can enter mode 1.

In mode 1, the APES will turn off its navigation systems including the IR sensors and the motors for propulsion and will become stationary. Now it will be able to see the cat, and power on its show laser diode and the motors for the lens system and grating system. The show laser movement is an algorithm that will be explained at a later point along with the lens and grating system. During mode 1, the camera will need to be able to identify both the cat and the laser simultaneously so the algorithm for its movement will work. If the cat somehow moves away from the camera's field of view, then the mode one will need to deactivate and turn off the show laser. The APES will move into mode 2 as search mode was practically activated during mode 1 and does not need to be reactivated again. This schematic provides the general plan of the sequence that the APES will follow on startup. Modes 1 and 2 each have more complicated algorithms associated with them that will need to be explained in detail with a different block diagram. This block diagram is what will be our intended design and may need to be altered considerably depending on how the project is doing.

## 5.3.3 Show Laser Movement Algorithm

The block diagram below represents what the show laser is supposed to do while it is mode 1. This is the intended function and will be the subject to be tested for the final demo. To start off, the camera will determine if it is possible to identify both the laser and cat with their respective positions. The position that is tracked is mainly just relative to the camera and what it sees. For instance, the camera has a 2D array that it stores as its vision/field of view. The laser's position if it was in the top left corner of the array would have its position stored there. If the cat was shown at the top right of the camera's field of view that is where its position will be stored. For determining difference of position, the middle pixel of the cat's position and laser's position will be used. The distance of pixels it is from these two middle pixels will be the positional difference that the camera will store for the next block.

The distance that was determined in pixel count can be determined as actual physical distance by approximation. The camera's total field of view will be roughly constant as the show laser will need to be close enough to see. The cat will be determined as near if its distance is within roughly one foot of the laser. This is when the show laser will move a certain distance. As shown, if the cat is above the laser, then it will move down. If the cat is to the right of the laser, it will move right. This certain distance will need to be determined and tested, but it can approximately 1 meter.

Figure 50 is a block diagram of more detail between mode 1 and the "search mode" of the APES algorithm. The search mode is when the camera is active and is actively trying to detect the cat in its FOV. The camera's time to attempt to find the cat should be roughly 30 seconds. If it cannot find the cat, it will go searching for it with its navigation system and algorithm's in mode 2. If the cat is found, then the avoidance mode activates that is detailed in Figure 50. During avoidance mode, the laser is in the camera's FOV only and if the cat for some reason leaves the camera's FOV or is unable to detect, the APES should go into mode 2 to navigate for the cat.

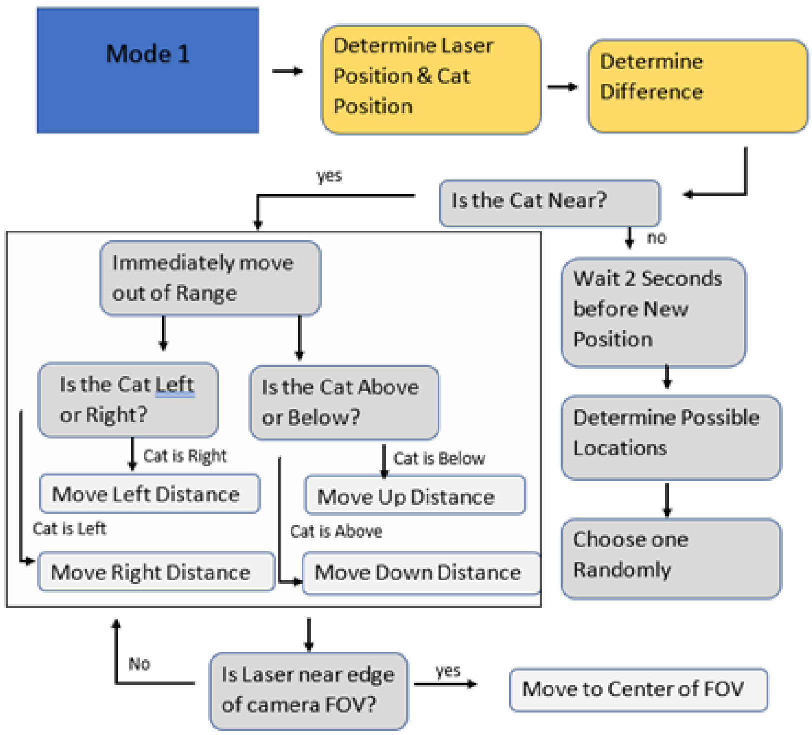


*Figure 50: Show Laser Movement Block Diagram*

While the camera is active and looking for the cat in search mode, the show laser should try to attract the cat, so it is active simultaneously. The movements it does to attract the cat are shown in the "patterns in FOV" section: a horizontal line movement, a vertical line movement, a square-shaped movement, a circle-shaped movement, and a full rotation around the entire device. The full rotation movement means the laser beam moves out of the camera's FOV while the rest of the patterns are all within the FOV. Patterns may be added or removed based on their complexity or demand on the servos.

# 5.4 Software Design

The APES will run using a raspberry pi 3b and Arduino working in tandem to help it accomplish its primary objectives of detection and navigation.

Upon starting the APES, we will initialize our primary sensors and simply ping each one to see if they are up and reporting readings back to the microprocessors. For

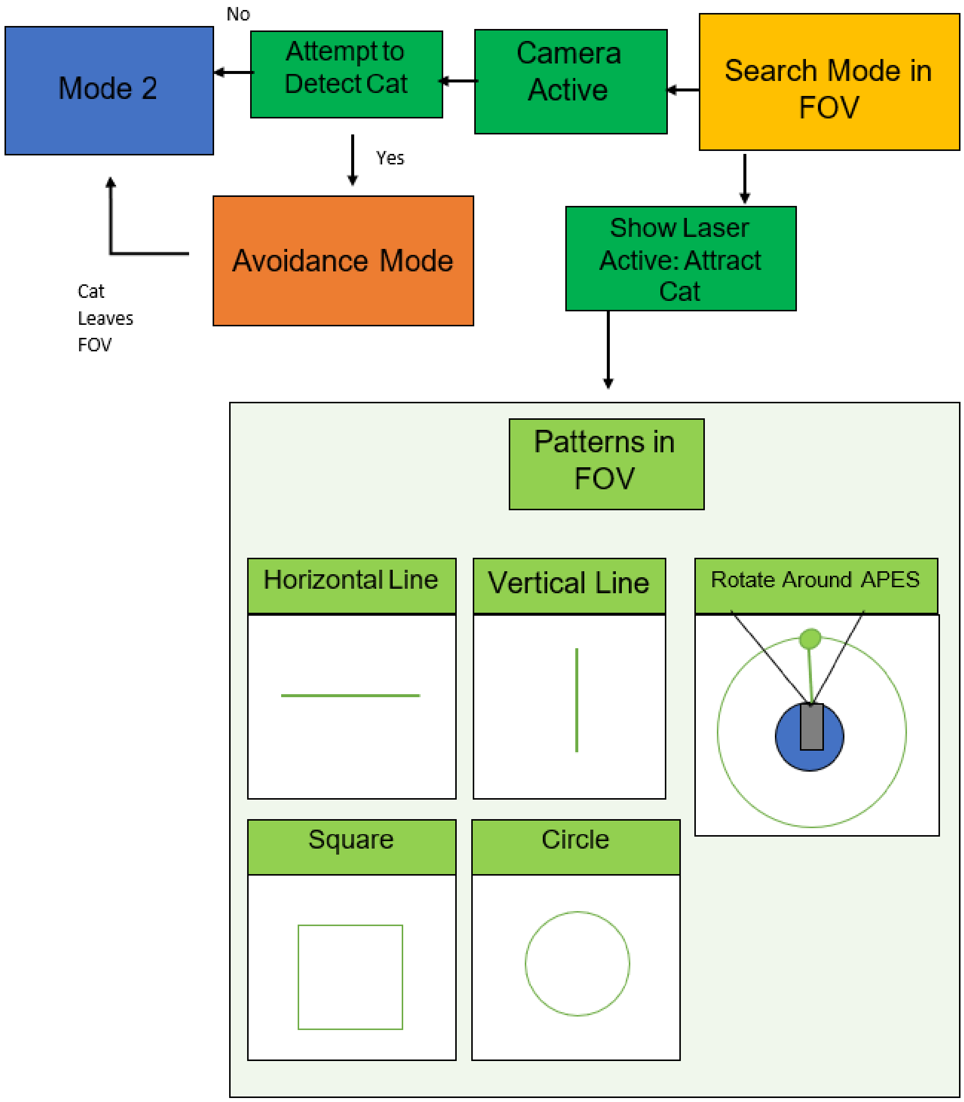


*Figure 51: Search Mode Block Diagram*

pi this will include initializing the camera and making sure it can capture frames, while for the Arduino this will include motor checks, servo checks, and sensor detections. Once initialization is complete the APES will attempt to seek out the user's pet to engage with it. It will begin by scanning its surroundings visually and if the pet is detected engaging in entertainment, and if not, it will search for the pet by navigating to a new area and scanning again. Figure 52 gives an overview of the software's startup.

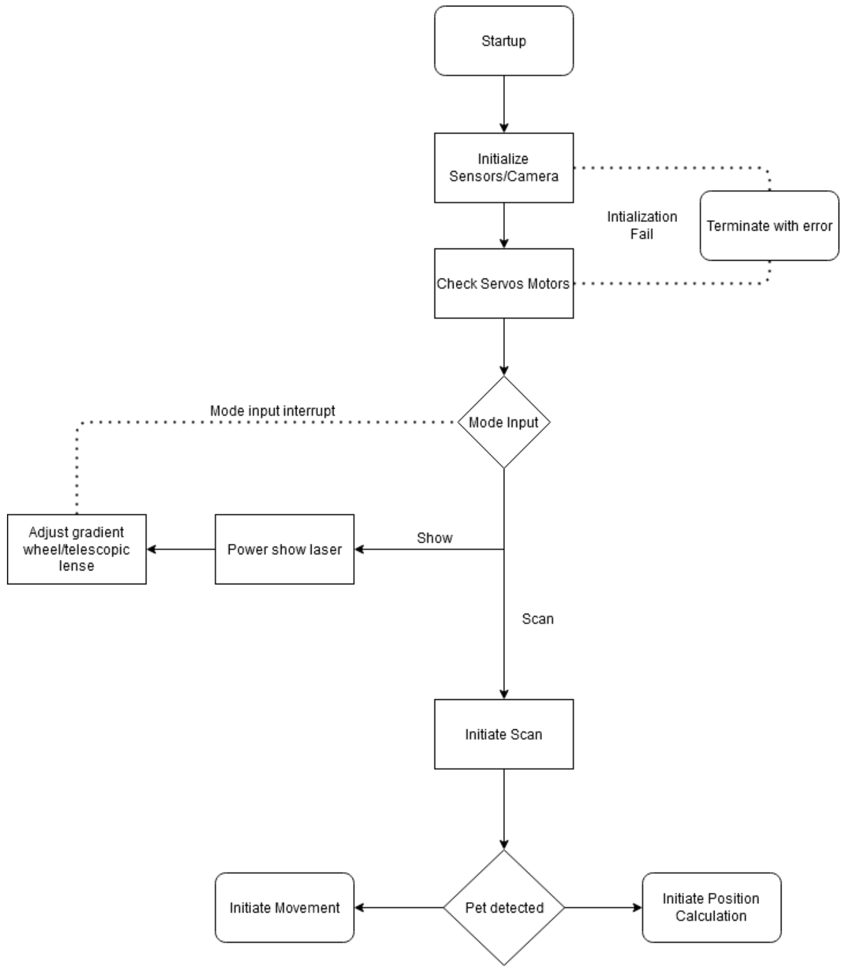


*Figure 52: Software Startup Flowchart*

**Vision**

One of the primary features of the APES is to use computer vision to identify the user's pet. To accomplish this, we will be using a raspberry pi connected to a webcam to act as a visual sensor that will take in video data and use said data to identify and track the subject. To accomplish this task the pi will have to carry out 3 functions. One of the primary features of the APES is to use computer vision to identify the user's pet. To accomplish this, we will be using a raspberry pi connected to a webcam to act as a visual sensor that will take in video data and use said data to identify and track the subject. To accomplish this task the pi will have to carry out 3 functions.

- First it must communicate with the webcam to receive video data in the form of frames.
- Next it must be able to interpret this data to determine the position of the pet.
- Finally, it must translate this data to the mounted show laser so it can move accordingly.

The communication of the webcam and the Raspberry Pi is simple enough. Our DORHEA Cam Module is specifically designed to attach to the camera connection mounted on the 3B's SOC. Calling the VideoCapture() class allows for the Raspberry Pi to receive data from the camera. The function uses a member read() function to capture and read a single frame from the video stream that has been opened via the open() member function. Once read the method returns the image data of the frame as a matrix of values that can parsed on worked on like any matrix of value. It is this matrix of values that the program will use to process the data.

After the frame data is captured, we will use the libraries available in openCV to calculate the position of the pet. This is where the processing of the video data takes place. Each frame will be analyzed one at a time first by gray scaling to create a light level mapping of the image. The light level mapping is crucial because the classifier uses this map to detect features on the image, light level mapping can be extremely volatile and is dependent on having clearly lit area that, so the varying features of the image are distinguishable from one another. Our goal is to have our cascade properly trained to distinguish the subject in varying environments and light levels. Once the image is gray scaled, we can run the cascade classifier on the image. In short, the cascade classifier is an algorithm that we train to detect certain features inside an image. Our goal is to have a classifier that can detect cat like objects in a variety of environments, to do this we will train our classifier using an Adaboost algorithm on different example and non-example images. The more the algorithm is trained and if done properly the better it should be at detecting the location of the cat. Once trained the cascade will be able to isolate a position on the image frame and store this as a value inside the program. It is this position value we will use to determine whether the laser is in a valid position or not.

Once the position is captured the final role of the vision algorithm is to use this position to determine the position of the show laser. To accomplish this we will explicitly mount the show laser close to the camera. This will allow the show laser to have a similar frame of reference for the room as the camera. When the position data is captured will we check the program for the position of the show laser by checking the angle of the servos it will be mounted to. Since to the camera the world appears as a 2D plane of varying light levels we can actually map the show lasers servo position to the plane of the camera's vision. We can then check the position of the cat given to us by the camera and cross reference that position with the current position of the lasers. We will create a minimum radius value that we will compare their distance value to. If it's greater than that median radius we will not change the lasers position, however if it is, we will use a direction value to move the laser away from the detected pet.

**Video Processing**

To process our video data, we will be using the Open CV library for Python. We will create an object in OCV to capture our video and store the frames at a certain interval. This interval must be long enough as to not clog the raspberry pi with unnecessary and expensive images in memory, while short enough to detect to a reasonable degree shifts in motion inside our video feed. Using OCV we will attempt to identify the users pet using a cascade classifier algorithm that will detect the user's pet with respect to the environment. The typical algorithm for feature detection is the Haar features and Cascade classifiers. These deep learning algorithms can be trained to detect features inside an image frame by being provided. In short feature algorithms use differences in light intensity as seen in Figure 53 to compare differences in light intensity we expect to what we find in the image [3]. These expected intensities are called features and we apply them to the image to determine if we are looking at the object we desire or not.

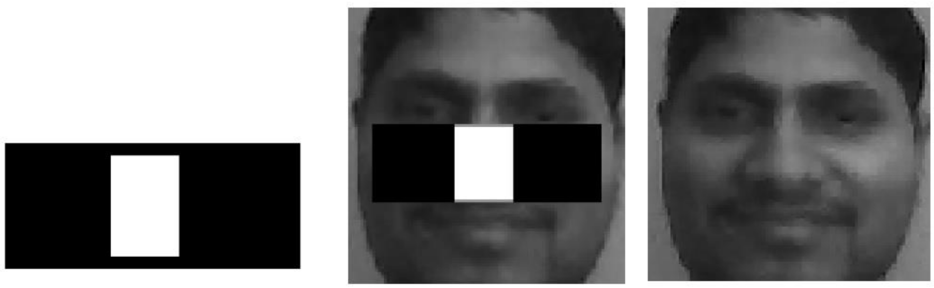

*Figure 53: Adaboost Example*

Applying these mappings over many images that are positive and negative examples of the object we desire we can train our algorithm to detect the object to a certain degree of certainty. [4]

By training the appropriate cascade we can simply call the cascade upon our frames to detect in real time whether the object, in this case the user's pet, appears in frame in not. We will then use changes in the subject's position to determine how the other subsystems inside the project should react.

In the design of the software with openCV we begin by taking in an input from image container which what we call upon in the core namespace of the program labeled cv. The language will automatically allocate memory for the input of images and output of functions at most times, such that if a function has more than one input array the input array and output array will be allocated at the same time.

Images will be read using the imread() function built into the basic library of openCV at about 1 image every 25 frames. These gaps in the frames will allow us to process images smoothly without filling up the memory of the system with data that is not of consequence.

Next, we will create a detection using a cascade for detecting the features of the desired object. We will create a grayscale of the images we feed the image processor. And then the cascade algorithm will be trained to detect the correct set of features on the gray scaled image.  Figure 54 gives a basic outline of how the detection function, cat_ext_cascade.detechMultiScale() will work.

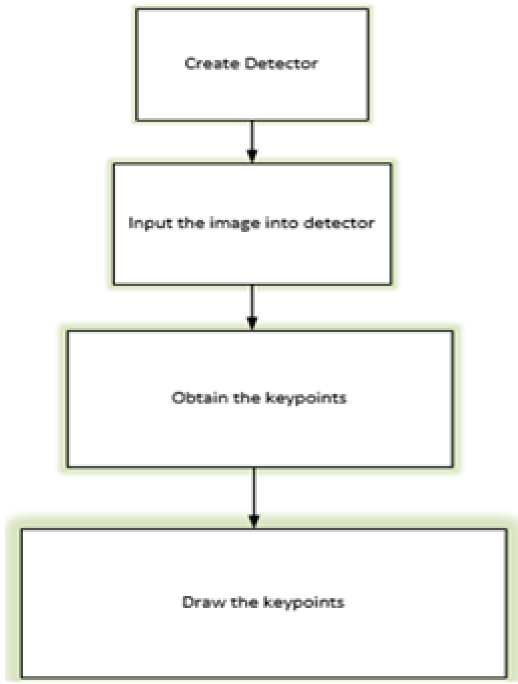


*Figure 54: Object Detection Flowchart*

The cascade will have to be specifically trained to detect the pet, while there exist specific libraries inherent to openCV that allows for the detection of people and faces, and cat faces humorously enough, detection of specifically a cat will have to be trained manually. The adaboost algorithm uses classifiers to that are trained to classify a specific set of features in gray scaled frame and determine whether they should be marked as an example of the object or not. This is done by running a varying convolution on the parts of the image that convert image data to a value, and then based on the values, guesses at whether or not the values correctly correspond as an example of the object we are looking. If the expert infers correctly it is chosen as a classifier for future image processing. Once enough iterations have passed, we can then test the classifier on real life examples by using it in our cascade functions. If the classifier is well trained, then it should reliably be able to point out the position of whatever object it was trained to detect when it appears on camera.

This training requires the use of example images and non-example images. In our case we will be using images of cats in varied environments to train our classifier.

To train it for accuracy we will be using images of smaller objects in similar environments that are not cats. It is extremely difficult for classifiers to differentiate between similar looking animals. This is because the final product of a classifier is simply an out of the object that is being sought after, so things with similar silhouettes such as cats and dogs will more likely than be detected as one another. Although we plan on training to be as accurate as possible it is advised to let users know that the toy can easily be tricked. We hope to train the algorithm on at least one hundred positive and one hundred negative examples. But depending on the accuracy more examples and iterations may be necessary.

Once we have the algorithm trained to a reliable degree, we can use the cascade to detect the position of the cat in the room as a tangible value. To the camera the view appears as a two-dimensional matrix of values. When scaled, the cat will encompass a certain area in the matrix, and we can capture this area to as x and y coordinates. These coordinates are what we will use as a reference for the laser to determine where exactly the laser should be pointed. By keeping the laser and camera in similar locations we map shifts in the laser in such a way that it avoids being within the same area that is covered by the detected cat.

**Position Calculations**

Using OpenCV we can not only determine if our subject is on but also their position in the frame. We can then calculate where the laser should point to in relationship to subject. This can be accomplished by implementing a sort of inverse tracking where instead of adjusting the servos to point the laser at the target we have the servos keep the laser a certain distance from the target. This can be done through the raspberry pi by calculating an angle for the servos to point to and outputting that to the servos themselves or can be calculated then serialized and passed via USB to the Arduino who will then adjust the servos itself.

1. Determine position using getLoc() function
2. Convert that data to an array of possible positions for the servos
3. Hash the position data from getLoc() to the array
4. Use value stored in that position to adjust servos redirecting the beam to the correct location

getLoc() is a place holder name for the function we will use to determine the position of the cat. If you ever used a cellphone to take selfies, you have witnessed computer vision determining the position of an object in a frame. This data will be captured by our program and sent to the microcontroller. Once the data reaches our Raspberry Pi we will need to translate into something usable by the program. The area of the image determined to encompass the detected pet will be given a set of coordinates. We will also have a set of coordinates that encompass that represent the current position of the laser.

It is critical to understand that the raspberry pi has no way of determining whether the laser itself is present within the frame of the image so it will be critical of us to properly determine through testing both an optimal range in which the feline is to be detected and engaged with and the optimal adjustments that correspond to the data given by the camera. To accomplish this, we intend to create a matrix that will correspond with image and contain all the positional data. We will cross-reference this matrix with the data captured by the camera to determine at which values in the matrix can be considered within the cat. We will then use check which point in the matrix the laser is currently located. Using the distance formula, we will determine whether the laser falls within the encompassed radius of the cat. If so, we will then move the laser at the opposite angle away from the center of the cat's position. Once an appropriate distance away we will store the lasers new position inside that point in the array and update the lasers data value to reflect. Inside each position in the array will be stored the servo values of that position in the array and whether this position is encompassed by the cat.

We will attempt to maximize the accuracy of these position locations such that the Raspberry pi can simply access these positions quickly and adjust the laser by simply reading the values contained within. Since this reading and adjustment may happen multiple times in a second, we must guarantee our algorithm is efficient. Figure 55 shows a quick overview of how this system will run.

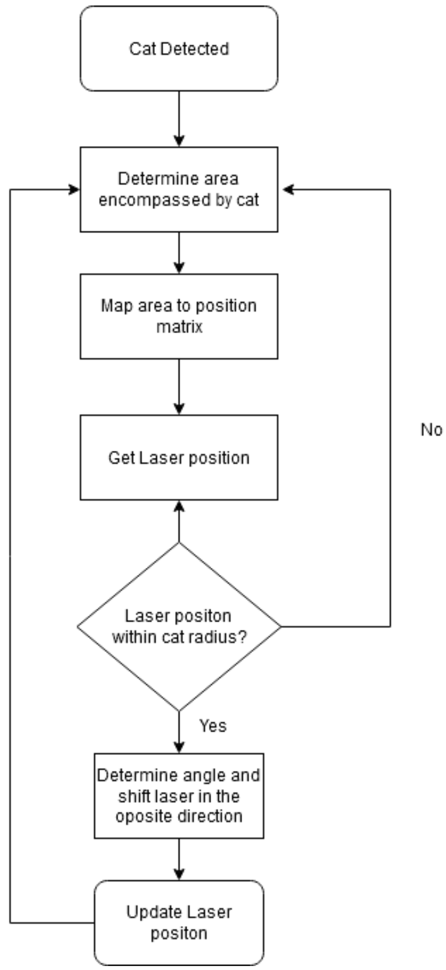


*Figure 55: Position Calculation Algorithm*

**Navigation**

Navigation will primarily be handled by the Arduino uno. Raspberry pi will pass to the Arduino whether or not the user's pet has been detected and if after a certain number of attempts to detect the pet, the APES will attempt to search for the pet by relocating to a new position. While in transit the optic sensors on the edge of the system will relay to the Arduino whether an object is in range of the system. By singling out which sensor has reported an object in range we can determine the direction the object is in and adjust the course of movement by sending to the steering servos an angle to turn the wheels of system. After a certain distance has been traversed, determined via timer, we will again attempt to scan for the pet. To guarantee that navigation is accomplished smoothly the APES will also have a gyroscopic sensor that returns the current angle of the APES. If this sensor is knocked off balance it will send an interrupt to the Arduino immediately shutting down the system.

The APES will be mounted on two motor powered wheels, these motors will have to be provided with an appropriate signal to operate. The microcontroller will read input data provided by the optical sensors to determine the position of the system in relation to its environment and move accordingly. The first being the laser range finder which will send out a laser signal straight ahead of the system and use the photodiode sensors to read the delay between the signals emission and the rebounding signals detection. This will drive the motion of the system by having these sensors report back any obstructions in the path of the system. The microcontroller will then communicate with wheels motors to begin motion by sending a pulse with modulation signal out of the controller and to the motor. By sending a PWM signal with a certain duty cycle, time in which the signal is on, we will be able to control the speed in which the system accelerates and decelerates. We will accomplish this with a formula that relates the reading of the photodiodes with the duty cycle of the pulse signal to give the system real time feedback on its motion. By combining this with the communication with the laser range finder, the system can determine how far away an object is and begin to stop by using a formula that takes in distance and converts it to the appropriate PWM signal we can have the motor accelerate and decelerate smoothly depending on how far away an object appears. While not intended to move and detect motion at the same time, perfection of smooth motion during navigation could open the door to increased features inside the APES.

The rangefinder also allows for if the system is suddenly obstructed can also be told to move in reverse before doing any more movement actions until there is enough distance for it to resume its normal movement routine. The system will be able to rotate in place just like a Roomba and should navigate the room in a similar two-dimensional fashion. This will be accomplished by sending opposite signals to the motors allowing it to spin in place.  Navigation will take place over a certain distance; in the event the distance of travel is lost it will also be on a timer before reverting to scanning mode. The ATmega328 comes with a built-in timer we will initialize before navigation starts and will send an interrupt signal after around 30 seconds of navigation. At top speed this should allow the APES to navigate around at least 10-20 feet away from its initial position During navigation the camera will be off, and the primary function of the raspberry pi will be to do any calculations, such brake speed and acceleration, that might slow down the ATMega. Further testing is needed but if power allows an extended navigational goal would be the ability to scan while in motion. While difficult due to the nature of computer vision, any bump could disrupt the vision of the camera and prevent it from detecting, the improvement will allow us to streamline the detection.

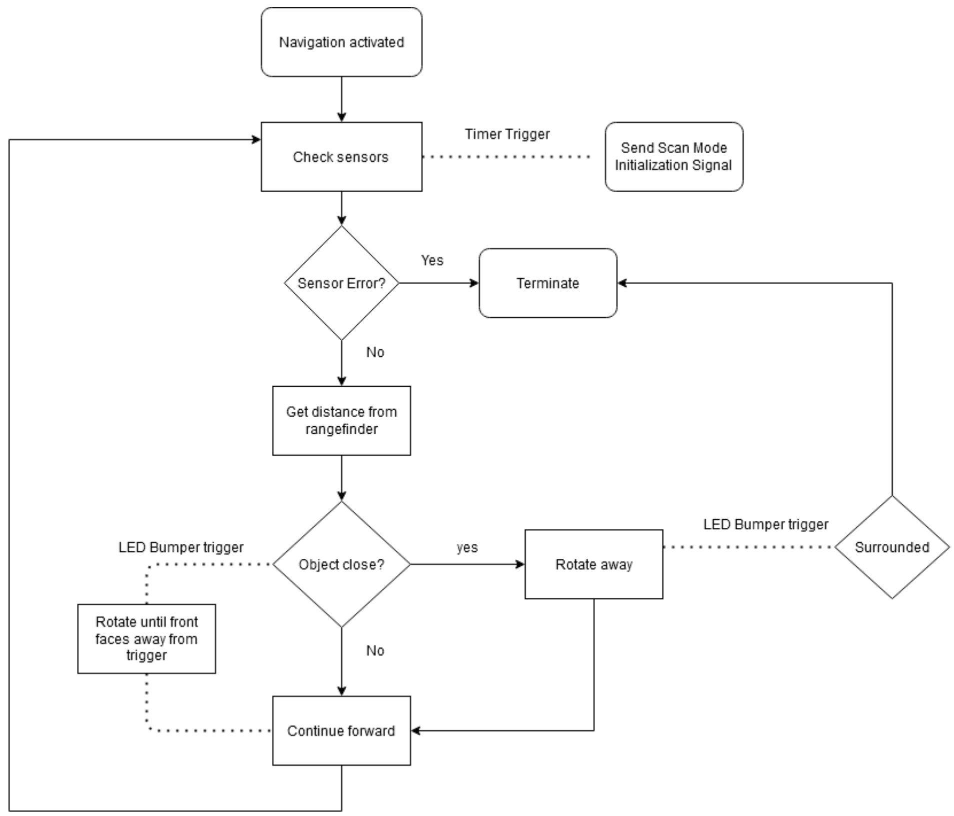


*Figure 56: Navigation Algorithm Flowchart*

# 6 Project Prototype Construction and Coding

This chapter includes information regarding the plans for the assembly and programming of the prototype including PCB development and general construction.

## 6.1 Integrated Schematics

This section will discuss and illustrate the circuits that are to be included on the Printed Circuit Board as well as the general wiring of the various components included in this project.

### 6.1.1 Voltage Regulator

The voltage regulator is a crucial circuit in any board design. The purpose is the ensure that the processor receives no more or less voltage than intended. These are necessary because if the voltage is not constant than the processor will be damages and the entire toy becomes little more than a paperweight with a battery or, in worst case scenarios, turns into a major fire hazard. The processor that needs to be powered by this regulator is the ATmega328 found on the Arduino UNO development board. To gain an understanding of what this processor needs to function properly we turn to what is currently used by the Arduino UNO board.

The Arduino UNO power system is comprised of two main sections: the voltage regulator and the multiple input management system. The voltage regulator is designed to supply a constant 5V to the ATmega328, which is the logic voltage required by many components designed to be used with Arduino development boards. This 5V is regulated by a low-drop-out voltage regulator. This means that a higher input voltage is supplied and stepped down to 5V. The particular regulator used by the Arduino UNO is designed to supply 5V with inputs from 6-12V. The input to this regulator is accessed via the barrel connector on the board or from the Vin pin of the power extension rail. The output of the regulator is sent both to the processor on the board and the 5V pin on the power extension rail for use by accessories.

The multiple input management system is included because the Arduino UNO board can be powered by either the barrel connector or the USB connection on the board. This selection system ensures that there is only one power source in use at a time because having both supplying voltages would result in a catastrophic power surge and destroy the processor. The multiple input management system consists of a simple logic gate that determines if there is sufficient voltage supplied by the regulator in which case the voltage regulator’s output will be used. If there is not enough voltage from the regulator it will turn to the USB power line which is already regulated. In whichever case, the data line from the USB input is preserved to allow for easy reprogramming of the board without having to disconnect the other power source. [7]

Since this project is to be powered by four AA batteries, both a voltage regulator and a multiple input selection system are not needed. There will only be one input that that will be passed through a voltage regulator. The four AA batteries' output varies from 6.6V (fully charged) to 4.8V (depleted). Thus, to enable the toy to use the greatest amount of power from the battery supply a voltage regulator is needed that can produce a steady 5V from an input both greater and smaller than 5V. This type of regulator is called a buck-boost regulator.

Buck-boost voltage regulators are a combination of buck regulators which step voltage down to the desired output and boost regulators that step voltage up to the desired output. The final design for the voltage regulator will be created using the TI WEBENCH power designer tool. This allows for a large number of regulators to be designed based on key parameters including the minimum and maximum input voltages, the desired output voltage, the maximum output current, and design considerations for the efficiency, cost, or footprint of the device.

For this toy, the TPS63070RNMR buck-boost voltage regulator was selected and is shown in Figure 57. This regulator outputs 5V at .15A from an input range of 4.8-6.6V. The device has 96.5% steady state efficiency and has a cost of less $2.

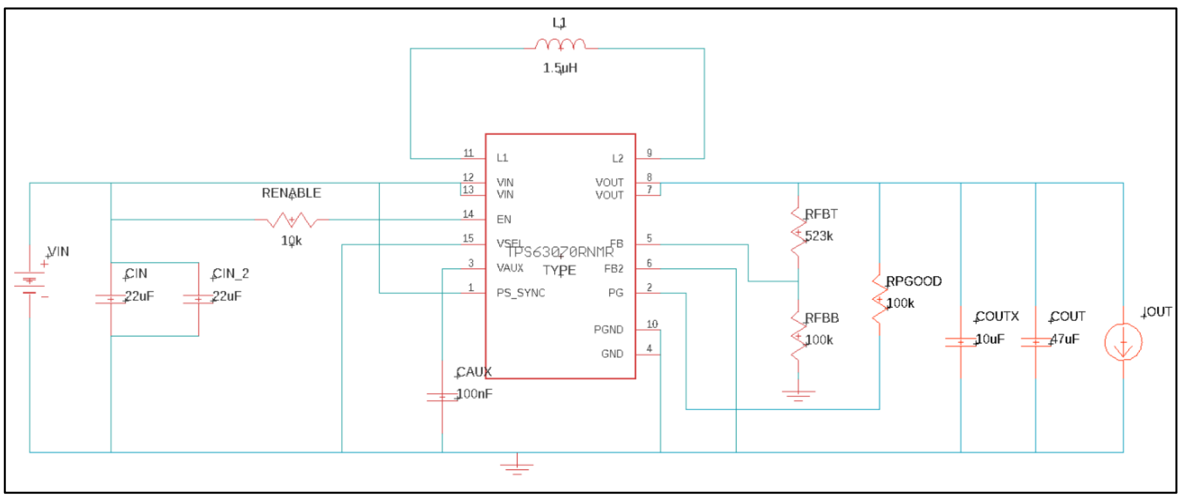


*Figure 57: TPS63070RNMR Buck-Boost Voltage Regulator*

## 6.1.2 ATmega328 Interfacing

Many different components and sensors being used by this toy are powered and controlled by the ATmega328. These include the LSM6DS33 gyroscope and accelerometer, the show laser diode, the L298N motor driver, and all of the DZS Elec Infrared Obstacle Avoidance Sensor Modules. There is also a small interface for communication between the ATmega328 and the Raspberry Pi.

The LSM6DS33 is running on 5V just like the ATmega328 so the power can be tied directly to the output of the voltage regulator. There are two connections to the ATmega328 itself: the SDA and SCL. This is how the LSM6DS33 chip will communicate its sensor readings to the ATmega328. The chip will be mounted to one set of female header pins and a pair of standoffs at about the center of the finished PCB. This will be to ensure the LSM6DS33 gets the best reading about overall device orientation that it can.

The show laser diode will be powered via a single GPIO pin on the ATmega328. Since the ATmega328 uses 5V logic, this allows a GPIO pin to be used a digital switch to control the show laser diode. This will be a vital function to ensure the safety of the device while in use.

The L298N motor driver requires nine total connections. Three of which are power related: a 5V connection is required to run the logic on the L298N, ground, and a higher voltage connection to power the motors. This higher voltage connection is tied directly to the positive terminal of the battery connections before voltage regulation. The other six connections are made to the GPIO pins of the ATmega328. The “int” pins are arbitrary in their connection but the enable lines for each motor must be connected to PWM capable pins in order to work properly.

The DZS Elec Infrared Obstacle Avoidance Sensor Modules are among the simplest devices to connect. The all run on 5V logic and can thus be attached to the output of the voltage regulator and ground. The third pins on the modules are each attached to their own GPIO pin of the ATmega328. This ensures that the program can distinguish between the different sensors to make an accurate decision on which way to navigate. All of these connections are displayed in the schematic in Figure 58. The connections are represented as pin headers, but the final printed circuit board may implement them as simple solder pads to attach wires.

Also included in the schematic is a power indication LED tied directly to the output of the voltage regulator. This will only be used as a status indicator during testing. One will also notice the small capacitor tied to the Vcc of the ATmega328. This capacitor is a bypass capacitor which will ensure that any noise in the form of AC voltage will be shunted to ground rather than interfering with the microcontroller itself.

Both of the schematics in this section were developed using Fusion 360. This software is the same that will be used in the creation of PCB and like its predecessor, EAGLE, streamlines the process from schematic to circuit board.

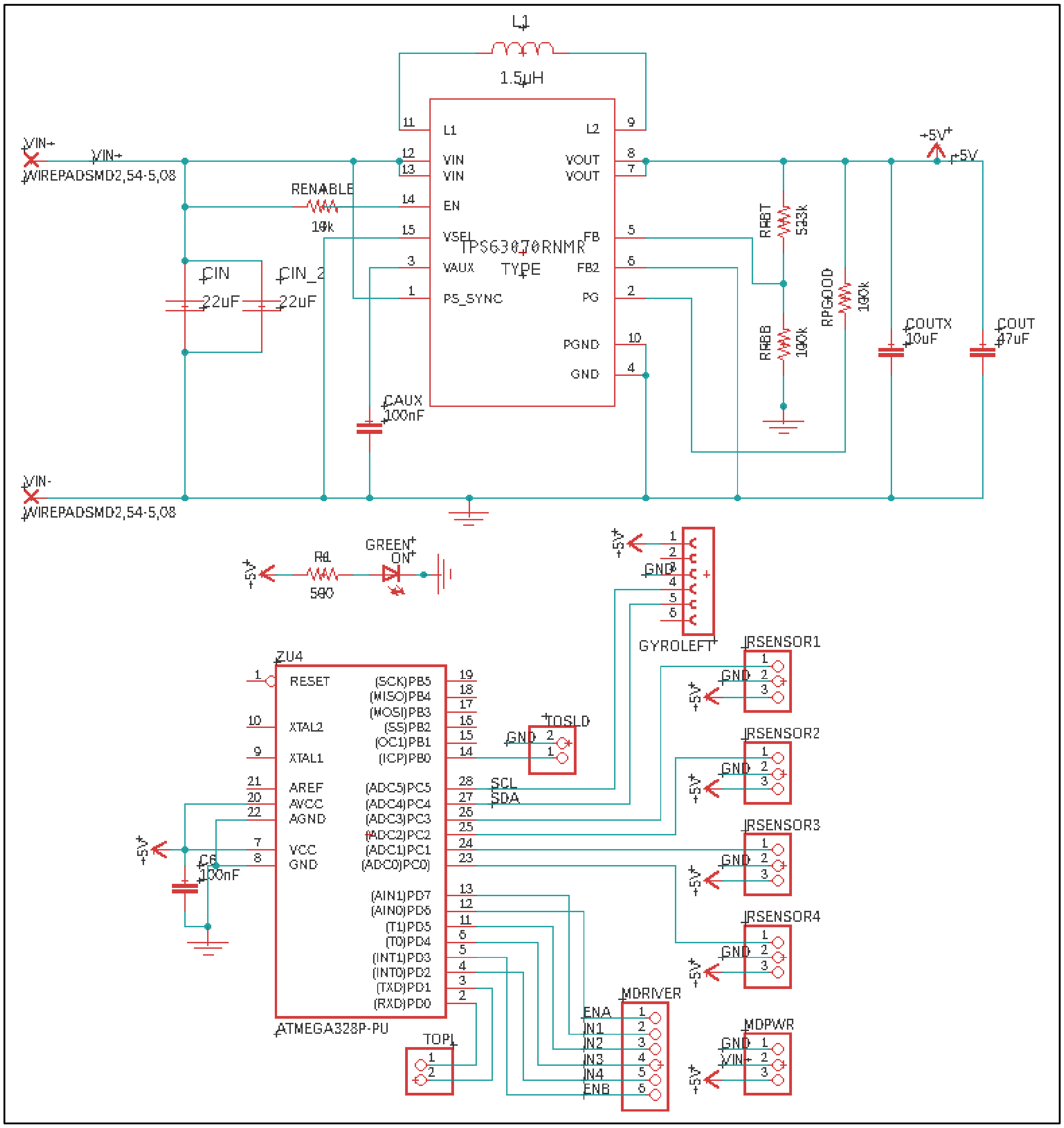


*Figure 58: ATmega328 Interfacing Schematic*

Table 10 is the Bill of Materials (BOM) for the schematic in Figure 58. Due to availability, the surface mounted parts are a mixture of 0805 (2012 metric) and 0603. It can also be seen that the TPS63070RNMR voltage regulator is listed as unavailable. While this does reflect the availability from larger manufacturers, there is some availability from smaller manufacturers. This will be taken into account when ordering a PCB. If the TPS63070RNMR remains unavailable when ordering, then other voltage regulators may be considered.

*Table 10: Bill of Materials*

| Quantity | Value | Package | Manufacturer | Manuf. Code | Availability | Price |
|---|---|---|---|---|---|---|
| **2** | 100nF | CAPC2012 X110 | MULTICOMP PRO | MC0805B104K250 CT | 5857 | 0.007 |
| **2** | 22uF | 805 | TAIYO YUDEN | JMK212BJ226MG-T | 775 | 0.068 |
| **1** | 47uF | CAPC2012 X110 | MULTICOMP PRO | MC0805B474M16 0CT | 342 | 0.053 |
| **1** | 10uF | CAPC2012 X110 | KEMET | C0805C106K8PAC TU | 2219 | 0.209 |
| **1** | | FE06 | POLOLU ROBOTICS & ELECTRONICS | 1016 | 6 | 0.148 |
| **5** | PINHD-1X3 | 1X03 | MULTICOMP PRO | 2211S-03G | 66332 | 0.019 |
| **1** | 1.5uH | SDR0805 | ABRACON | ASMPH-1008-1R5M-T | 3000 | 0.105 |
| **1** | PINHD-1X6 | 1X06 | MULTICOMP PRO | 2211S-06G | 21281 | 0.039 |
| **1** | GREEN | CHIP-LED0805 | LUMEX | SML-LX0805GC-TR | 3000 | 0.053 |
| **1** | 500 | RESC2012 X65 | VISHAY | CRCW0805499RF KEAHP | 2717 | 0.032 |
| **1** | 10k | RESC2012 X65 | VISHAY | CRCW080510K0F KTA | 50937 | 0.017 |
| **2** | 100k | RESC2012 X65 | VISHAY | CRCW0805100KJN EA | 5000 | 0.005 |
| **1** | 523k | RESC2012 X65 | VISHAY | CRCW0603523KF KEA. | 20000 | 0.002 |
| **2** | PINHD-1X2 | 1X02 | MULTICOMP PRO | 2211S-02G | 251421 | 0.014 |
| **1** | TPS630 70RNM R | RNM0015 A | TEXAS INSTRUMENTS | TPS63070RNMR | 0 | 2.23 |
| **1** | ATMEG A328P-PU | DIL28-3 | MICROCHIP | ATMEGA328P-PU | 1832 | 1.76 |

# 6.2 Printed Circuit Board

A key component of the design process for a project involving electrical engineering is the design of the printed circuit board (PCB). This is one of the components that separates our project from that of a hobbyist who decided to make a gadget using a standard development board. The design and creation of the PCB are the next steps in the development process: stripping away unnecessary parts and features from a development board, leaving only the connections required to complete the given task, and creating a PCB to house the processor and all of these vital circuits.

The schematics shown in section 6.1 which relate to any components and systems controlled by the ATMEGA326 microcontroller will be consolidated onto the final PCB. The Raspberry Pi 3 that is used to control the camera and show laser servos will remain as-is. This is because the Raspberry Pi 3 is a microprocessor; a significantly more complex development environment which a simpler PCB can be constructed for however, time constraints do not allow this kind of work.

The final schematic and board layout will be developed during the beginning of Senior Design 2 or during the Winter break. The plan for development, ordering, and assembly are detailed in this section.

## 6.2.1 PCB Design

**Software**
The initial plan for PCB development was for this to be done using the Autodesk EAGLE software. This plan has shifted since Autodesk decided to move towards an all-encompassing product development software known as Fusion 360. This software allows for products to undergo a significant portion of the development process without ever switching programs. It is assumed that this software package now includes the features of EAGLE and the original software is no longer available. Given that Autodesk provides students to use their software free of charge, Fusion 360 will be the software of choice for developing the PCB and any CAD work that needs to be done.

Once the design of the PCB is finished, it will be exported in a set of files called GERBERs. These are used by board manufacturers to accurately fabricate the digital design in real space. The files are simply a map that lays out the features and locations desired by the designer. The RS-274X or extended Gerber is the current format preferred by manufacturers and as such will be used by this team.

The specific file types that will be used include the Copper Top and Bottom (.cmp and .sol) files. This pair of files map the copper features of the board which only include the traces. These appear on both the top and bottom of the board, hence the need for two files.

Since the copper traces on the PCB are laid out in a two-dimensional fashion, a key goal when designing the PCB is to keep the traces from crossing. This however is not always possible and to accommodate this, there is included a drill legend (.drd) to map out vias and other holes in the board. Vias are small holes drilled in the PCB that can connect any layer of the board to another. This allows for a third dimension to be used when laying out the copper traces of the board. This should still be minimized because vias are not always as reliable as traces. The drill legend also maps out other holes to be drilled such as mounting holes. These are holes drilled typically in the corners of the board which are meant to have screws or other attachment methods fed through them to allow the board to be secured to a surface.

The top and bottom soldermasks (.stc and .sts) are thin layers of polymer applied over top of the copper traces. These protect the copper from oxidizing, and they separate the copper from any solder that they may otherwise come in contact with. Stray solder could be catastrophic due to the delicate nature of circuitry. It could pose a serious safety hazard to both the parts and the user if any traces are unintentionally shorted. In many applications only one solder mask is required since components are only attached to one side. This will be the intent when designing our PCB.

Another layer specified in files are the top and bottom Silkscreen (.plc and .pls). These files are the maps for the (typically white) text that appears on both the top and bottom of most PCBs. One main function of this text is to identify where specific parts are supposed to be placed on the board. Generally called "reference designators", these small annotations not only assist in the assembly of the board but also with the engineer working with the finished product. Knowing where each component resides without having to access the original PCB design files allows for significantly simplified troubleshooting.

## 6.2.2 PCB Fabrication and Assembly

Once the design of the PCB has been finalized, the files listed above will be sent to a PCB manufacturing facility. The specific facility has not yet been selected since the cost and shipping times will depend on the complexity and dimensions of the final board. Based solely on estimates, the likely candidates include in no particular order: AISLER, OSH Park, OurPCB, and BasicPCB. [5]

Once the board has been fabricated, it will need to undergo the assembly process. This begins with a stencil made out stainless steel through which solder paste will be applied. The solder paste is a grey, viscous, liquid which contains small balls of metal called solder and flux. The flux helps the metal to melt when heated. This paste must be applied in exact locations in exact amounts in order for the PCB to work properly, this is where the stencil comes in. The stencil is used to allow for the paste to be applied properly.

Now that the paste is applied, the components must be mounted. A pick and place machine is essentially an automated pair tweezers that lift and deposit each surface mounted part onto the board and solder paste. With the parts now mounted in the solder paste, the paste itself must be solidified. This is achieved through the process of reflow soldering. The PCB is placed on a conveyer belt and moved through a series of ovens. The first set of ovens are at slowly increasing temperature culminating around 480 degrees Fahrenheit. Once the solder has been melted, the PCB continues through another series of ovens set to decreasing temperatures so that the solder can solidify evenly and in a controlled fashion.

Once the PCB has been cooled, they are inspected and tested in various ways. Both manual and automated inspections ensure that the board has been assembled properly. The board is put through many electrical tests to make sure that all of the components are functioning properly and if any of these tests are failed, the board is recycled or scrapped, depending on the company.

If the PCB passes all inspections and testing it is then cleared to be cleaned. There is a significant amount of residue left over from the assembly process and that can cause both aesthetic and functional issues with time. The PCB is washed using deionized water to remove all residue. There is no threat to the PCB or any of the components by using deionized water since water itself does not damage electronics. The ions found in regular water is what allows current to pass through it and if the water is deionized then this cannot happen. After the PCB has been cleaned and dried, it is now ready to be packaged and shipped to the customer. [6]

This process is generally done by a separate facility than the manufacturing however there are some companies that will both manufacture and assemble the boards. This is preferred since it eliminates any shipping time to and from the manufacturer to the assembler however can come at a higher price. Assembly houses are still be researched and will be identified closer to the completion of our PCB design.

# 7 Project Prototype Testing

While it has become exceptionally difficult to develop a plan with the presence of the pandemic, our team has been able to work around the many restrictions in place in order to test both hardware and software to be incorporated into the prototype.

## 7.1 Hardware Testing

Due to the ongoing COVID-19 pandemic, hardware testing will primarily be conducted outside of standard laboratories. The university has provided an Analog Discovery 2 system to students to do a majority of electrical and computer hardware testing outside of the traditional laboratories. Optical hardware testing will primarily be done in student laboratories within the CREOL building when available for students.

Testing the optic and photonic components of our design will require a standard optical laboratory arrangement. An ideal optical testing environment would be a room with positive air pressure flow to minimize the presence of dust and other airborne particles that could interfere with measurements. Additionally, the environment should have the ability to turn off any room lighting to minimize noise generated by said lighting. A standard optical laboratory consists of a leveled and clean optical table along with various mechanical and electrical equipment for table mounting and power. There should be a computer with appropriate processing power to compute and analyze collected optical data from oscilloscopes, spectrometers, and cameras.

### 7.1.1 Infrared Proximity Sensor Testing

The DZS Elec Infrared Obstacle Avoidance Sensor Modules are to be used as navigational sensors for the APES. Their purpose is to notify the ATmega328 when an object comes closer than a specified distance so that the course can be adjusted.

**Objective/Background**
The purpose of testing these sensors is to ensure that they can be tuned to detect objects at a particular distance and that they are working properly. These sensors have three header pins: 3-5V VCC, ground, and a digital output pin. They are powered by either the 3.3V or 5V pins of the ATmega328 and return a simple digital signal: 1 for object detected, 0 for no object detected. On the sensor module is a potentiometer used to tune the detection distance of the sensors. There is also a pair of status LEDs, one for power and one for object detection indication.

**Equipment**

DZS Elec Infrared Obstacle Avoidance Sensor Modules
Arduino UNO R3 development board
3 Male to Female Jumper Wires
A flat object to be detected
Ruler

**Setup**

A short testing program was written for the Arduino UNO that turns on one of the onboard LEDs when an object is within detection range and flashed to the development board.

The ground pin is connected to the ground of the Arduino UNO, the VCC pin is connected to the 5V pin of the Arduino, and the output pin is connected to the software specified GPIO pin.

**Testing Procedure**

1. Check all connections are not loose and are plugged into the correct terminal.
2. Align the sensors so that the LED and photodiode are parallel to the desk and ruler.
3. Adjust the potentiometer to the point that the sensor does not detect anything.
4. Place the object to be detected 2 inches from the senor and adjust the potentiometer until just before the object is detected.
5. Slowly move the object closer to the sensor until it is detected and adjust the potentiometer so that it is just under the level of detection.
    a. Repeat until the sensor no longer detects any object, the distance prior to this measurement is the minimum detectable distance
6. Place the object 4 inches from the sensor and adjust the potentiometer until it is just detected.
7. Move the object vertically in and out of the line of sight of the sensor to confirm the object is actually being detected.
    a. Move the object farther away (at least to where it is not detected) and repeat step 5 until moving the object has no effect on detection. This is the maximum detectable distance.

**Conclusion**

The manufacturer’s description of the sensor modules says that they can detect objects from 2–30cm or .787-11.8in.

Table 11 shows that the sensors on average were not as sensitive at closer distances than the manufacturers claim but tended to exceed the specification on the farther distance. Since the intended use for these sensors is to be in the 6-8in range, all sensors will work as needed.

*Table 11: IR Sensor Test Results*

| IR Sensor | Minimum Detectable Distance (inches) | Maximum Detectable Distance (inches) |
|---|---|---|
| **1** | 1.1875 | 19 |
| **2** | .6875 | 15.1875 |
| **3** | 1.1875 | 11 |
| **4** | 1.9375 | 19 |
| **5** | .9375 | 19 |
| **6** | 1.1875 | 8 |
| **Average** | **1.1875** | **15.198** |

## 7.1.2 Gyroscope Testing

The LSM6DS33 is the chip to be used as a means for determining the orientation of this toy. This will use both the accelerometer and the gyroscope data to calculate the angle along a specified axis on which the device resides.

**Objective/Background**

The purpose of testing this sensor is to ensure that the calculations can be made in a fast, efficient manner to determine the current angle of the device along either the X or Y direction. Only these two axes are required because they represent the planes parallel to the floor, which this angle is relative to. This data is crucial to the safe operation of the toy because in the event that the toy is inverted, the show laser must immediately be deactivated to keep it from pointing at an upward angle.

**Equipment**

Adafruit LSM6DS33 Breakout Board
Arduino UNO R3 development board
4 Male to Male Jumper Wires
A flat surface
Protractor

**Setup**

A small testing program was written that takes in the raw data from the chip and converts it to angle relative to the flat surface the LSM6DS33 resides on. This is done using complimentary filtering to help account for the drift of the gyroscope. Lying flat on the desk corresponds to 180°.

This program was flashed to the Arduino UNO R3 development board and jumper wires were installed connecting the SDA, SCL, and GND of each respective board. The Vin pin of the LSM6DS33 was then connected to the 5V pin of the Arduino UNO.

**Testing Procedure**

1. Check all connections are not loose and are plugged into the correct terminal.
2. Hold the LSM6DS33 flat against a surface, with the protractor held vertically against the side of the chip so that the angle in the Y axis can be observed.
3. Reset the Arduino board and clear the serial monitor output.
4. Once incoming data can be seen in the serial monitor:
   a. Hold the LSM6DS33 flat on the table for two seconds
   b. Tilt the LSM6DS33 90° in either direction along the Y axis
5. Repeat with the X axis

**Conclusion**

As can be seen in the plots in Figure 59, the filtering algorithm used to calculate the angle of the LSM6DS33 still needs to be refined. This is evidenced by the

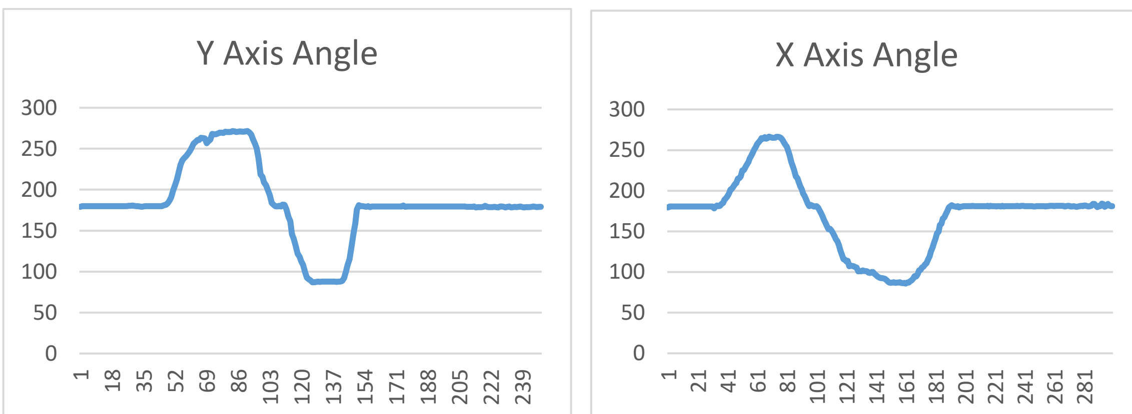


*Figure 59: LSM6DS33 Testing Results*

presence of some noise on the angle plots and the slight gyroscope drift still present. These can be addressed during final implementation and this test can be considered a success.

## 7.1.3 Motor Testing

The TT motors and the Dual H Bridge L298N motor driver will be the basis of the locomotive subsystem of this toy. The Dual H Bridge L298N will be connected to an ATmega328 which will control the input to the motors.

**Objective/Background**

The purpose of this test is to ensure that both of the L298N chips that were purchased work as intended and to determine how consistent in speed the two TT motors that were purchased are. This is vital to determine if the parts are viable as well as how the inconsistencies can be addressed in the final implementation. The L298N's use six pins from the ATmega328 each, not including the three power connections. At least two of these pins must be PWM capable to allow for speed control of the motors.

**Equipment**
Dual H Bridge L298N Motor Drivers
TT Motors
Arduino UNO R3 development board
Breadboard
9 Jumper Wires
Wheels
Tape

**Setup**
A testing program was written for the Arduino UNO that will cause both motors to turn on at a specified speed for 10 seconds. The TT motors are then connected to the L298N motor ports.

The jumpers connected to the motor enable pins are removed and each of the L298N pins are connected to the GPIO pins specified in the testing program. The 5V pin of the Arduino UNO is connected to the 5V pin of the L298N, GND is connected to GND, and the Arduino UNO's Vin pin is connected to the L298N's 12V pin. Attach the wheels to the TT motor and mark with tape one spot on each tire tread. Label each motor as A or B as well as each L298N.

**Testing Procedure**
1. Check all connections are not loose and are plugged into the correct terminals.
2. Align the wheels on the motors such that the taped spots are in the same location relative to the motor.
3. Run the testing program and count how many rotations the wheel on motor A makes.
    a. Repeat, counting the rotations of motor B
4. Repeat three times for each speed
5. Increase the speed of the motors and repeat until the maximum speed has been tested.
6. Repeat with the second L298N.

**Conclusion**
Adafruit's website warns that the TT motors will have inconsistencies from motor to motor. This has been confirmed as shown in Table 12 and can be corrected to ensure that both motors move at the correct desired speed at any given time during final implementation. Both of the Dual H Bridge L298N motor drivers perform well. This has been a successful test.

*Table 12: Motor Testing Results*

| | Driver A | | | | | Driver B | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Speed | 150.00 | 175.00 | 200.00 | 225.00 | 255.00 | 150.00 | 175.00 | 200.00 | 225.00 | 255.00 |
| | Motor A | | | | | | | | | |
| A1 | 15.50 | 17.00 | 18.75 | 19.38 | 21.38 | 16.50 | 18.00 | 18.38 | 19.25 | 20.63 |
| A2 | 16.50 | 17.25 | 18.75 | 19.63 | 21.50 | 16.38 | 19.00 | 18.13 | 19.25 | 20.25 |
| A3 | 17.13 | 18.00 | 18.75 | 20.13 | 21.75 | 16.75 | 19.25 | 18.38 | 19.25 | 20.50 |
| **A average** | **16.38** | **17.42** | **18.75** | **19.71** | **21.54** | **16.54** | **18.75** | **18.29** | **19.25** | **20.46** |
| **A RPM** | **98.25** | **104.50** | **112.50** | **118.25** | **129.25** | **99.25** | **112.50** | **109.75** | **115.50** | **122.75** |
| | Motor B | | | | | | | | | |
| B1 | 13.50 | 15.25 | 18.25 | 18.50 | 20.50 | DNS | 16.50 | 17.50 | 19.50 | 21.13 |
| B2 | 15.75 | 16.00 | 18.25 | 18.63 | 19.63 | DNS | 17.63 | 17.50 | 20.50 | 21.13 |
| B3 | 15.75 | 16.75 | 17.50 | 19.13 | 21.63 | DNS | 17.00 | 17.75 | 20.00 | 20.50 |
| **B average** | **15.00** | **16.00** | **18.00** | **18.75** | **20.58** | **N/A** | **17.04** | **17.58** | **20.00** | **20.92** |
| **B RPM** | **90.00** | **96.00** | **108.00** | **112.50** | **123.50** | **N/A** | **102.25** | **105.50** | **120.00** | **125.50** |

# 7.1.4 Laser Rangefinder Testing

To test our rangefinder, we must first measure the performance of the components of the device to see if they meet standards set by the provided data sheet. The laser rangefinder consists of two primary components: Laser Diodes and Photodiodes.

**Photodiodes**
With our laser diodes tested, we move on to testing the next main component of the laser range finder: the photodiodes. There are two main attributes to test for in photodiodes:

- Responsivity
- Sensitivity

**Photodiode Responsivity Testing**

**Objective/Background**
Photodiodes are the components within our rangefinder that will detect the return beam to determine an angle. The device must be able to efficiently detect the wavelength of light found within the rangefinder's laser beam. Additionally, the photodiodes must be able to discern the light emitted by the IR LEDs on the device well enough from the rangefinder's laser to operate correctly.

**Equipment**
Photodiode
A Breadboard
Components for a driver circuit for the photodiode device
2 High precision Multimeters
IR light source (One for laser wavelength and one for LED wavelength)

Optical Power Meter
Convex Lens
Spectrometer

**Setup**

The testing materials should be placed on a flat, nonconductive surface in an environment with minimum lighting needed. Arrange the photodiode and its complementary driver circuit on the breadboard. Assemble the driver circuit to include one multimeter to measure the current through the photodiode line and another to measure voltage across the driver load. Activate the IR light source being used. Using the spectrometer, measure the peak output wavelengths of the light to assure they match the wavelengths of the laser and the IR LEDs. Align the light source so that it is pointed directly at the photodiode chip. Use a convex lens to focus the light as finely as possible on the photodiode. Assure that the optical power meter can be placed in the beam path to measure the light source's output power

**Testing Procedure**

1. Turn off the light source aimed at the photodiode
2. Record the current in the system. This is the photodiode's dark current, typically in the order of microamps.
3. Turn the light source back on. Assure that the emitted light is the wavelength of either the laser or LED with the spectrometer.
4. Adjust the output power of the light source to approximately 1 mW of optical power. This can be measured with the optical power meter.
5. Record the voltage across the driver load and the current in the circuit of the photodiode.
6. Continue to repeat steps 4 and 5 while increasing the output power of the light source in increments of 0.5 mW until 7 mW is reached.
7. Switch the output wavelength of the light source to that of the untested wavelength in respect to either the LED or laser. Repeat steps 4 through 6 for this new wavelength.
8. Take the collected data and subtract every current measurement by the dark current found in step 2.
9. Find the generated electrical power of the system by finding the product of the voltage and recalculated current at each optical power for each data set.
10. Plot the voltage generated versus the optical power for each wavelength. Plot the electrical power generated versus the optical power used.
11. Compare the processed data to which wavelength generated more voltage and power.

**Photodiode Sensitivity Testing**

Objective/Background

The photodiodes used in the rangefinder will need to detect the return beam at a power idealistically equivalent to the initial output or lower than the initial laser output. It is imperative to see how sensitive our photodiodes are to the wavelength of the laser beam. In other words, how much optical power is needed to hit the photodiode in order to detect a signal. Finding this will allow us to determine a threshold power for our signal. Additionally, photodiodes have a limit to their electronic power generation known as the saturation limit. These results can be used to find the saturation of the device corresponding to the incident optical power.

**Equipment**
Photodiode
A Breadboard
Components for a driver circuit for the photodiode device
2 High precision Multimeters
IR light source (For laser wavelength)
Optical Power Meter
Convex Lens
Spectrometer

**Setup**
The testing materials should be placed on a flat, nonconductive surface in an environment with minimum lighting needed. Arrange the photodiode and its complementary driver circuit on the breadboard. Assemble the driver circuit to include one multimeter to measure the current through the photodiode line and another to measure voltage across the driver load. Activate the IR light source being used. Using the spectrometer, measure the peak output wavelengths of the light to assure it matches the wavelength of the laser. Align the light source so that it is pointed directly at the photodiode chip. Use a convex lens to focus the light as finely as possible on the photodiode. Assure that the optical power meter can be placed in the beam path to measure the light source's output power

**Testing Procedure**
1. Turn off the light source aimed at the photodiode
2. Record the current in the system. This is the photodiode's dark current, typically in the order of microamps.
3. Turn the light source back on. Assure that the emitted light is the wavelength of either the laser or LED with the spectrometer.
4. Adjust the output power of the light source to approximately 0.5 mW of optical power. This can be measured with the optical power meter.
5. Record the voltage across the driver load and the current in the circuit of the photodiode.
6. Continue to repeat steps 4 and 5 while increasing the output power of the light source in increments of 0.5 mW until 10 mW is reached.
7. Take the collected data and subtract every current measurement by the dark current found in step 2.

8. Plot the voltage generated versus the optical power.
9. If the driver circuit has a reverse voltage, the resulting graph should be linear. If not, the graph should be exponential. Regardless, there should be a point where the line slope plateaus. This point is the saturation limit of the device.

**Polarizer Effectiveness Testing**

**Objective/Background**

Polarizers are optical devices meant to change the polarization of incident light. Given that our light source is a laser beam, the output light is already linearly polarized. Since we have a linear polarized light source and a linear polarizer, we can use Malus's law to get a specific optical power we want. This needs to be possible as our rangefinder laser has a stronger output power than our set safety standard. Confirming that our polarizer can effectively use Malus's law will allow us to use our rangefinder laser safely. It is also important

**Equipment**

Polarizer
1064 nm Laser
Laser driver (if needed)
Optical Power Meter
Convex Lens

**Setup**

The testing materials should be placed on a flat surface in an environment with minimum lighting needed. Set the laser to be operated at a consistent output optical power. Arrange the laser, polarizer, and optical power meter in a straight beam path in the order listed. Use a convex lens to focus the light as finely as possible from the polarizer to the optical power meter.

**Testing Procedure**

1. Turn on the laser.
2. Remove the polarizer in the beam path.
3. Record the reading on the optical power meter. This is the laser's maximum power.
4. Replace the polarizer in the beam path.
5. Rotate the polarizer until the optical power meter drops to nearly 0 W. Record the position of the polarizer. This is the position at which the beam and the polarizer are crossed at 90°.
6. From the previous position, rotate the polarizer 90° in any direction. Record the optical power at this new position. This is the maximum power transmission through the polarizer.
7. From the previous position, rotate the polarizer 45° in any direction. Record the optical power at this position. This position should only allow half the max optical output through.

8. Take the maximum optical power found in step 3 and subtract it by the value found in step 6. This is the total polarizer loss.

## Rangefinder Angle Accuracy Testing

### Objective/Background
With all the individual components of the rangefinder tested, the assembled apparatus must be tested as well. The rangefinder component finds distance by using angles and trigonometric properties. Our ability to accurately determine these needed angles effects the overall performance of the system. Therefore, we must test to see if our angles are accurate enough for distance measurement.

### Equipment
A Flat Level Surface
An Object with a Width greater than 1 in
Laser Rangefinder Device
Protractor

### Setup
The device should be placed on a flat level surface and the chosen object at a distance of about 2 ft in front of the device. To view collected data, a computer with software able to connect to the APES microcontroller should be connected in order to view retrieved data.

### Testing Procedure
1. Point the front of the Laser Rangefinder towards the location of where the object is.
2. For one of the servos, place the protractor above the motor.
3. Align either the measuring tape or meter stick with the object and the top of the protractor on the rangefinder.
4. The chosen measuring device should align with an angle on the protractor. Record this angle.
5. Remove the protractor and measuring device from the rangefinder device.
6. Activate the device and allow it to operate one complete scan.
7. Collect the angular data outputted by the device to the microprocessor.
8. Move the object to a new angle from the device.
9. Repeat steps 1 through 8 several times.
10. Once data for one servo is complete, repeat steps 1 through 9 for the other unmeasured servo on the rangefinder device.
11. Using the collected data, find the percent error of the actual and measured distance for each data set.
12. Plot the data percent error versus the actual angle.

**Rangefinder Performance Accuracy Testing**

**Objective/Background**

The purpose of the rangefinder is to be able to accurately determine the distance from the front of the device to an object on front of it. Testing is required to see how well the device can perform this task before mounting it on the assembled chassis. Collected data will be used to determine of the rangefinder is effective enough at range finding to be used on the APES system.

**Equipment**

A Flat Level Surface
An Object with a Width greater than 1 in
Laser Rangefinder Device
Meter Stick or Tape Measure

**Setup**

The device should be placed on a flat level surface and the chosen object at about 2 ft in front of the device. To view collected data, a computer with software able to connect to the APES microcontroller should be connected in order to view retrieved data.

**Testing Procedure**

1. Point the front of the Laser Rangefinder towards the location of where the object is.
2. Using the meter stick or tape measure, measure the exact distance from the center of the rangefinder in between the two diodes.
3. Activate the device and allow it to operate one complete scan.
4. Collect the distance data outputted by the device to the microprocessor.
5. Move the object or device about 6 inches further apart.
6. Repeat steps 1 through 5 several times.
7. Using the collected data, find the percent error of the actual and measured distance for each data set.
8. Plot the data percent error versus the actual distance.

## 7.1.5 Show Laser Diode Testing

For the laser diodes used in the APES, the main specifications to test and verify are:

- wavelength,
- output power,
- divergence angle,
- magnification,
- output shapes.

As not all of the elements (i.e. laser diode, lenses, and diffraction gratings) have not been gathered yet, this section will be the plans regarding how to test these specifications once they have been collected.

## Wavelength and Output Power

**Objective/Background**
The wavelength and output power will help us determine which class of laser the LD will be in for our laser safety standards and constraints. The peak wavelength found will be the only wavelength considered that is emitted by the LD. The output power of the LD will be evaluated at the wavelength found and will be measured versus current supplied.

The output power be plotted and will result in a graph known as the power-current (P-I) curve. There are two regions of the P-I curve: the first region has low current and nearly no output emission, and the second region has visible laser light that scaled linearly with input current. The mode of operation for our LD will start in the second region. Our first point for our graph will start at the lowest amount of current needed for the second region (i.e. threshold current) and will have a few extra points above the initial point.

The output power is needed to balance the visibility, power consumption, and safety. For example, the schematic below shows a typical P-I curve of an LD. The mark at the threshold current will be the first measurement point as this is when it starts lasing.This in turn increases the visibility which is an important aspect that needs to be high, but also increases our power consumption in mA which needs to be low. Additionally, for laser safety standards the maximum output of a visible class 2 laser is one mW, and five mW for class 3R. As the output power increases the class of the laser changes, so it will be best for the laser to not exceed five mW even in spite of visibility.

Out of the measurement points between the threshold current's output power and the maximum output power (i.e. five mW), we will have to determine the best point (or in-between point) for the mode of operation that accounts for visibility and power consumption. The visibility of the laser needs to be high as it will help with the camera's tracking and adjusting its movement and help with distracting the pets. Visibility still needs to be balanced as the light can be too bright and strain the eye when looked at. The power consumption, which is directly proportional to the supply current, needs to be low to lengthen the lifetime of the project per battery and produce less heat as the heat sink's quality can only maintain a stable current with respect to temperature.

**Equipment**
Spectrometer
Photodetector (power meter)

Laser Diode
Convex Lens

**Testing Procedure**

1. Align the laser diode to the optical fiber of the spectrometer on a flat surface.
2. Find and record the peak wavelength of the spectrum displayed in the software.
3. Align the laser diode to the power meter and place the convex lens a focal length away from power meter in between the laser diode and power meter.
4. Vary the current of the laser diode to the threshold current and record the current and optical power on power meter.
5. Incrementally increase the current up to the maximum optical power of 5 mW and record the current and optical power at each increment.

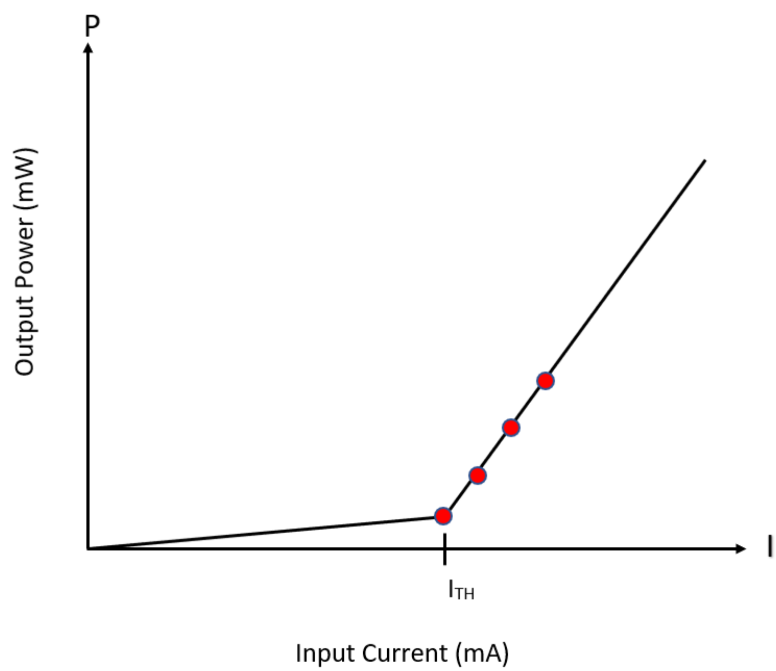


*Figure 60: General LD P-I Curve*

## Divergence Angle, Magnification and Output Shapes

**Objective/Background**

The beam's divergence angle will aid us in accomplishing the goal to produce distinct beam sizes at variable magnifications. The divergence angle can be tested by measuring the input beam diameter first then the output beam diameter at a fixed distance and using the respective equations to find magnification. As seen in the figure below, the divergence angle for the laser diode is related to the beam diameter by the following equation:

$$\theta = 2 \arctan(x/2y),$$

Where θ is the divergence angle, x is the diameter of the beam, and y is the distance of the beam.

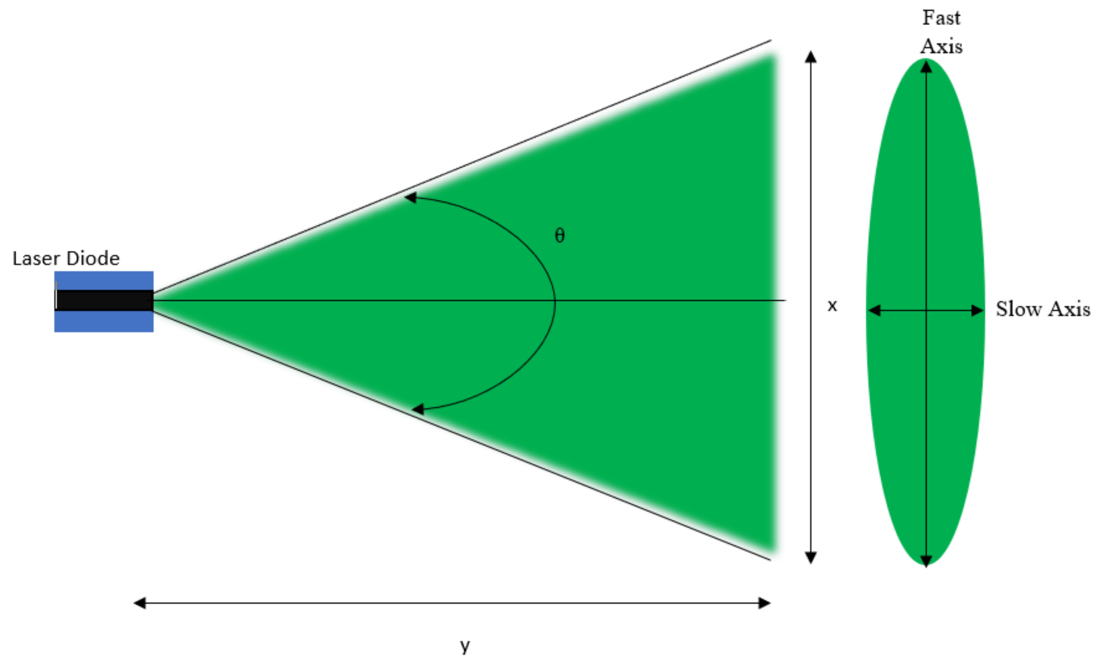


*Figure 61: LD Beam Divergence*

The main type of magnification we will observe is the angular magnification that is found by the ratios of the input and output divergence angles. Angular magnification deals with how large the object appears which is very important to our project in regards to visibility rather than how large the object is which is transverse magnification. The transverse magnification is found by the image and object ratio which will be the output beam diameter divided by the input beam diameter. At least five magnification ratios will be used including no magnification (1x) and maximum magnification, and the best ratios with the best output shape will be determined after testing. Both types of the magnification will be recorded, and their amounts may be adjusted to best fit our visibility criterion.

The laser diode has an elliptical beam shape from the diffraction of its aperture. This means there are two different axes that need to be accounted for: the "fast" axis which is the longer side of the oval shape and has the larger divergence angle, and the "slow" axis which is the short side and diverges slower. For our project, the difference of axes divergence angle will not be that impactful, but their measurements will need to be taken separately and their respective magnifications will both need to meet the requirements.

The output shape of the laser diode refers to its intensity profile or pattern that has been altered by the diffraction gratings and filters. The exact profile does not need to be measured (i.e., beam profiler measurement), but only the general shapes that the diffraction gratings yield will need to be observed. At least five distinct patterns will need to be generated excluding the initial beam shape with no gratings or filters.

There are two main types of patterns that can be generated: patterns made by diffraction gratings and combinations of them, and patterns made by unique or “special” gratings. Diffraction grating patterns yield only dots at regular intervals from a laser source, and by combining them (putting them together so the beam goes through more than one) more complex patterns can be generated. At least three distinct diffraction grating patterns will need to be observed, meaning no rotational symmetries or scaling factors are between them. Special gratings are not just periodic slits but take on forms that will yield a unique pattern such a star or crosshairs. The types of patterns that can be generated by these special gratings are endless, but for simplicity only one of them will be used at a time and at least two special patterns will need to be observed using these gratings. The types of unique gratings that will be included into this project is based on availability and convenience of its output shape.

**Equipment**
Laser Diode
Two Lenses (short and long focal length)
Diffraction Gratings
Ruler
Screen

**Testing Procedure**

1. Align the laser diode, a collimating lens and the screen so the beam passes through the lens and illuminates the screen. The collimating lens should be very close to the laser diode, and the screen should roughly be a few meters away from the collimating lens.
2. Measure the beam diameter which will be the input beam diameter.
3. Place the output lens in between the collimating lens (roughly a few cm away) and the screen to create the telescopic lens system.
4. Record the distance between the collimating lens and the output lens and the beam diameter on the screen. This is the output beam diameter.
5. Incrementally move the output lens and repeat step 4.
6. The maximum distance (last increment) between the collimating lens and the output lens is their added focal length and repeat step 4.
7. Move the output lens to the position where the output beam diameter is the same as the input beam diameter.
8. Align a diffraction grating in between the output lens and the screen.
9. Observe and record the general shape of the new pattern on the screen.

10. Vary output lens position to change magnification.
11. Repeat steps 8 and 9 with new diffraction gratings and combinations. Keep record of magnifications used respectively.

# 7.2 Software Testing

Testing is needed to determine if the program for our project is running correctly. The testing will primarily focus on the response time and data reading of the sensors along with the execution of the algorithm at varying stages of the program. To accomplish this will be testing the software with multiple test layers to ensure that each system responds correctly and scales up with the rest of the system. Each component will be need to a certain criterion to determine if it is capable of test load.

## 7.2.1 Environment

The software will be tested on the hardware expected to run it as to ensure there is no discrepancies between functionality during testing and functionality during operation. The testing of the camera will take place on the raspberry pi, the software will be programmed via Windows on an integrated development environment for accuracy in syntax and ran directly from the microprocessor to ensure its capabilities of accomplish the goals of the system.

## 7.2.2 Testing

**Start-up**

In order to make sure the system runs correctly it is key to make sure all subsystems are able to communicate with each other efficiently. The raspberry pi will be instructed to send some data to the ATmega328 to ensure that communication is established. The ATmega328 must respond or else the Raspberry Pi will not continue the program. This communication is absolutely critical to the operation of the project and is thus the first thing we must make sure is operational whenever the system is started. Further test for their communications is having each microprocessor give instructions for the operation of the other. The Raspberry Pi will drive the wheel motors and the ATmega the laser servos to guarantee that data is transmitted quickly and interpreted accurately by the other microcontroller.

**Communication**

The the raspberry pi will instruct the ATmega to read a small amount of data from each sensor and send it to the raspberry pi at which point the pi will output this data. To make sure communication is done smoothly and quickly we will attempt to read from each sensor during different modes of operation. While in motion, while at rest, and while other sensors are being operated. This will also test the power draw of the system and determine how many subsystems we can operate at once. The Raspberry Pi will then generate signals meant to elicit certain motion behaviors from the ATmega.

1. Send a signal to set the light bumper flags to elicit turning behaviors
2. Send signal to the gyro sensor to elicit shutdown behavior
3. Send signal to laser range finder to elicit turning behavior
4. Send signals to light bumper to elicit shutdown behavior

This ensures that the sensors are operational and confirms communication is sound. The ATmega will then send a pulse to each motor and servo to guarantee they are all connected and operating correctly. It will then ask the raspberry pi to read from the camera and transmit a confirmation back to ATmega which the microcontroller will output. These tests will ensure that both processors are able to communicate with one another and to all their respective sensors.

**Camera**

The camera will need to be tested to ensure it is properly recording and transmitting data to the microprocessor and that the microprocessor is interpreting said data correctly. To do this we will first need to train the algorithm on various objects as to ensure it capable of differentiating objects amongst different environments. We will have the camera identify still catlike images in an empty space and a cluttered space to ensure it can identify the subject in commonplace environments. We will have the camera attempt to identify a cat shaped object at varying light levels to determine what level of light is optimal for detection. We will use different colored objects to determine how the shade of the cat's fur might change the reaction of the camera to its presence. To test the noisiness of the cameras image We will move the servo that the camera is mounted to immediately prior to running the classifier and place in front of the camera a positive example, most likely a face, to determine the time it takes from the cessation of motion to a positive identification. If the camera is disturbed in anyway during operation, we want to be sure that this will not impede the function of the camera too much.

We will also test for the ability to track varying levels of motion by having the camera track objects of increasing speed. Cats can move up to 47km/hr so it is imperative that our camera is able to capture at a decent framerate, interpret that data quickly, and have the rest of the system respond in time. Having the raspberry pi output coordinates depending on the speed of the object and its location will allow us to make sure the system is keeping up with the demands of the project. Tracking a rolled ball as it passes by and having the servos keep the laser trained on it will replicate the exact motion we expect of a user's pet when approaching the system. The higher we can increase the velocity in which the system is able to correctly tract subjects the more responsive our system will be.

Finally, we will test the Raspberry Pi's positional tracking. To begin we will feed it varying spots in the image that it should avoid and have the algorithm find the spot in which the laser is safe. We will give a specific place to point the laser, if it accomplishes this we will then inverse this and feed it a positional matrix with only one position available for occupation. We want our position algorithm to find someplace where the laser can occupy as quickly and efficiently as possible. If we develop an algorithm that can parse the position matrix quickly and determine an open spot, then we can rest assured that the positional calculations won't lead to slowdown of the system.

.

# 8 Administrative Content

In this section we will discuss the administration of the project which includes a laying out of deadlines and expenses as to ensure proper time and fiscal management. We will list milestones to the project and the expected date we wish to have them completed by.

Figure 62 represents who takes responsibility for the primary goals of the APES. The primary goals are color-coded for division of labor and the joint colors mean the group members are expected to work together on it. While the goals listed here are for outward appearance, there are some subjects left out such as programming and power supply. The algorithms developed for the APES are under the autonomy section, and their responsibilities are respective to their goals.

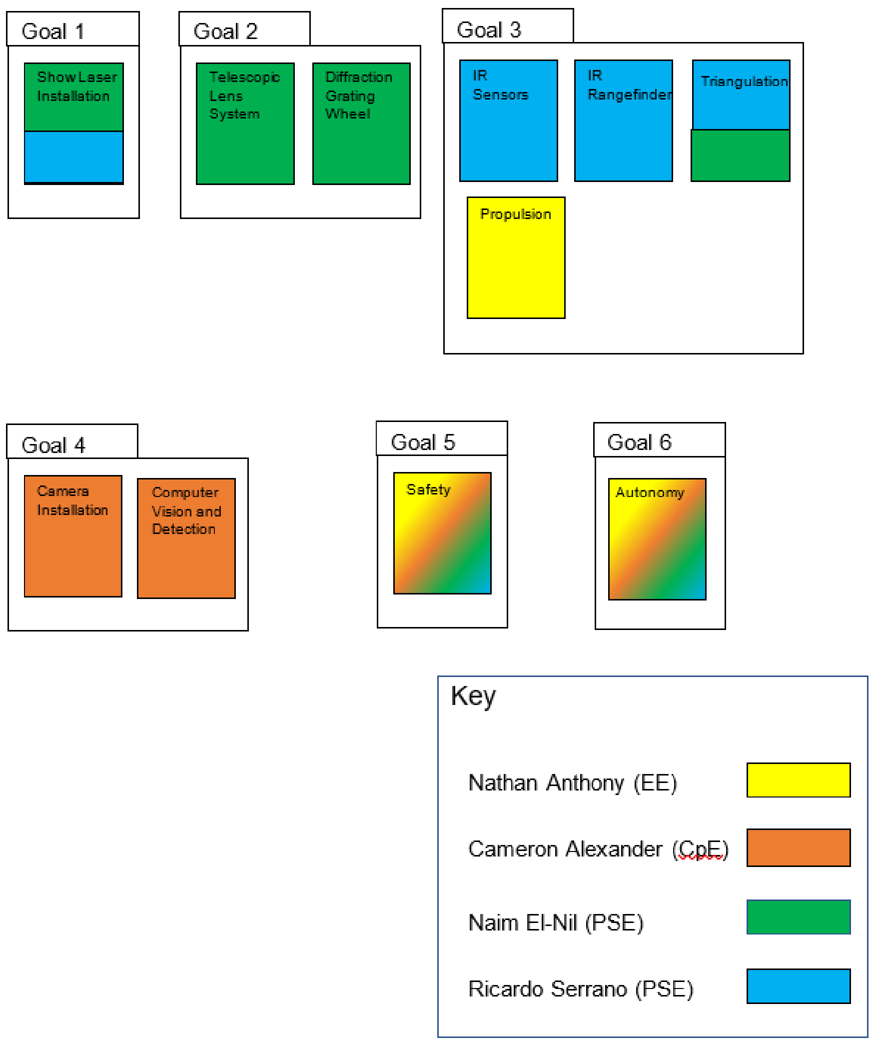


*Figure 62: Primary Goals Responsibility*

# 8.1 Milestone Discussion

Table 13 shows our milestones and the expected date of their completion, dates not yet determined will be marked TBD.

*Table 13: Milestones*

| | |
|---|---|
| **Senior Design 1** | |
| Idea | 8/28/2020 |
| Project Selection & Role Assignments | 9/4/2020 |
| Initial Document – Divide & Conquer | 9/18/2020 |
| First Draft | 11/13/2020 |
| Parts Selection | 11/13/2020 |
| Parts Ordered | 11/15/2020 |
| Document Review Meeting | 11/16/2020 |
| Second Draft | 11/27/2020 |
| **Final Document Due** | 12/8/2020 |
| **Senior Design 2** | |
| Assemble Prototype | 01/20/21 |
| Testing and Redesign | 2/28/21 |
| Finalize Prototype | 3/31/21 |
| Peer Report | TBD |
| **Final Documentation** | TBD |
| **Final Presentation** | TBD |

# 8.2 Budget and Finance Discussion

Table 14 lays out the part selection and cost of the project. The project will be funded by the team.

*Table 14: Component Prices*

| Part | Quantity | Vendor | Cost |
|---|---|---|---|
| **Raspberry Pi 3B** | 1 | Amazon.com | $32 |
| **Arduino UNO** | 1 | N/A | N/A |
| **Dorhea Raspberry Pi Cam** | 1 | Amazon.com | $9 |
| **DC Gearbox TT Motor** | 2 | Adafruit.com | $5.90 |
| **L298N Motor Drive Controller** | 1 | Amazon.com | $8.69 |
| **SG90S 9g Micro Servo** | 2 | Amazon.com | $9.99 |
| **Adafruit LSM6DS33** | 1 | Adafruit.com | $9.95 |
| **GHH PT Pan/Tilt Camera Platform** | 1 | Amazon.com | $8.49 |
| **6pc Optical Lens Set** | 1 | Amazon.com | $15.43 |
| **Diffraction Grating Slide-Linear 1000 Lines/mm 2x2** | | Amazon.com | $12.95 |

# Appendix A – References


[1] Julia Layton "How Robotic Vacuums Work" 3 November 2005. HowStuffWorks.com. https://electronics.howstuffworks.com/gadgets/home/robotic-vacuum.htm

[2] Damirchi, Mohammad. Arduino Buying Guide 2020: Complete Guide to Choose the Right Board. electropeak.com/learn/arduino-buying-guide-how-to-choose-right-arduino-board/#:~:text=Get to Know Arduino Components. 1 Processor. UNO,4 Power Supply. 5 Jack Adapter. More items.

[3] Cascade Classifier. (n.d.). Retrieved from https://docs.opencv.org/3.4/db/d28/tutorial_cascade_classifier.html

[4] (n.d.). Retrieved from https://ieeexplore.ieee.org/document/990517

[5] https://pcbshopper.com/

[6] "Printed Circuit Boards Assembly (PCBA) Process." PCBCart, www.pcbcart.com/article/content/pcb-assembly-process.html#:~:text= 1 Step 1: Solder Paste,place, they need to remain there. More .

[7] Hussaini, U. (2020, September 02). Core Subsystems - Understanding the Arduino Uno Power Supply. Retrieved from https://technobyte.org/arduino-uno-power-supply-arduino-hardware-core/#:~:text=Voltage Regulator Subsystem of the Arduino Uno. This,shields and other necessary components on the board.

[8] Methodshop.com. (2012, December 13). FroliCat BOLT Laser Pet Toy [video review]. Retrieved from https://www.flickr.com/photos/methodshop/8269836357/

[9] Lens. (2020, November 27). Retrieved from https://en.wikipedia.org/wiki/Lens

[10] How to build a beam expander. (n.d.). Retrieved from https://www.newport.com/n/how-to-build-a-beam-expander

[11] Anti-Reflection (AR) Coatings: Edmund Optics. (n.d.). Retrieved from https://www.edmundoptics.com/knowledge-center/application-notes/lasers/anti-reflection-coatings/

[12] Diffraction of Light. (n.d.). Retrieved from http://www.alternativephysics.org/book/Diffraction.htm

[13] Diffraction and Interference. (n.d.). Retrieved from http://electron6.phys.utk.edu/phys250/modules/module 1/diffraction_and_interference.htm

[14] Arduino. (n.d.). Retrieved from https://banshee.mx/etiquetas/arduino?page=7

[15] Pelayo, R. (2020, February 05). Arduino PID Control Tutorial. Retrieved from https://www.teachmemicro.com/arduino-pid-control-tutorial/

[16] Laser Standards and Classifications. (n.d.). Retrieved from https://www.rli.com/resources/articles/classification.aspx#:~:text=The IEC document 60825-1,the safety of laser products.&text=Class 2M lasers have wavelengths,below the Class 1M AEL

[17] West, M. (n.d.). Social Play in the Domestic Cat. Retrieved from https://academic.oup.com/icb/article/14/1/427/2066860

[18] Parker, W. B., Richard, R. P., Parker, R., & Richard, I. (2020, May 21). How Much Attention Do Cats Need a Day? Retrieved from https://www.seniorcatwellness.com/how-much-attention-do-cats-need-a-day/

[19] Fundamentals Of Lasers: Edmund Optics https://www.edmundoptics.com/knowledge-center/application-notes/lasers/fundamentals-of-lasers/

# Appendix B – Permissions

## Figure 5

**Approval details**

This photo is the work of Uwe Aranas . It is not in the public domain but protected by law. However, subject to the license below, it can be used by anyone free of charge.

- **Condition for free private and commercial use:**
  - **Mention of** the author in the form **"Photo by CEphoto, Uwe Aranas"** or alternatively **"© CEphoto, Uwe Aranas"** . The attribution must be clearly related to the picture. If this is not possible due to lack of space, please contact me before using it.
  - The work is passed on under the same conditions.
- **Not required, but desirable in the interests of fairness:**
  - Linking of the picture in online media with the original photo: https://commons.wikimedia.org/wiki/File:IRobot-Roomba-Top-view-01.jpg
  - Sending a specimen copy, an excerpt as a PDF or a message via the website where the photo is used

Please write an email to spam@aranas.de (please replace the word *spam* with *cephoto2020* ) if you

- need the photo in a higher resolution,
- need my address for sending a specimen copy,
- have further questions about license-compliant usage.

statistics

This file is under a license that is incompatible with the license terms of Facebook Inc. It is therefore not permitted to upload this file to their social networks such as **Facebook** or **Instagram** .

### You are free to:

**Share** — copy and redistribute the material in any medium or format

**Adapt** — remix, transform, and build upon the material for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

### Under the following terms:

**Attribution** — You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

**ShareAlike** — If you remix, transform, or build upon the material, you must distribute your contributions under the same license as the original.

**No additional restrictions** — You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.

## Figure 20, Figure 24, Figure 25, Figure 26

**Nathan** <nathan.anthony@knights.ucf.edu>
3:15 PM

To: support@adafruit.com

I am working on a Senior Engineering Design Project and would like to request permission to use images of the following products in a report:

Product ID: 3777, 4480, 3757, 3763, 3766

Thank you,
Nathan Anthony

**Nathan** <nathan.anthony@knights.ucf.edu>
3:22 PM

To: support@adafruit.com

To whom it may concern,

I am working on a Senior Engineering Design Project and would like to request permission to use images of the following products in a report:

Product ID: 2942, 1967

Thank you,
Nathan Anthony

**Adafruit Industries** <support@adafruit.com>
4:30 PM

To: Nathan

yep, all good.

Figure 16, Figure 19 ,Figure 23



Figure 22

| | |
|---|---|
| **Description** | 10mm LED |
| **Date** | 1 December 2009, 15:05:19 |
| **Source** | Flickr: 10mm LED - LED-10B |
| **Author** | oomlout |
| **Permission** (Reusing this file) | This image, which was originally posted to **Flickr**, was uploaded to Commons using **Flickr upload bot** on 24 December 2012, 14:01 by **Biomazi**. On that date, it was confirmed to be licensed under the terms of the license indicated.<br><br>This file is licensed under the Creative Commons Attribution-Share Alike 2.0 Generic license.<br><br>You are free:<br>• **to share** – to copy, distribute and transmit the work<br>• **to remix** – to adapt the work<br>Under the following conditions:<br>• **attribution** – You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.<br>• **share alike** – If you remix, transform, or build upon the material, you must distribute your contributions under the same or compatible license as the original. |