Detecting Explosive Material via Optical Systems Observing the Behavior of Bees

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1. Executive Summary

The Bee-Enabled Explosive Substance Tracer and Identification of Narcotic Goods (BEESTING) is a bomb-detecting system making use of the proboscises of the common honeybee in conjunction with machine learning and imaging systems to observe consistent, double checked results via redundant systems. Bees have impressive scent-based capabilities highly similar to that of dogs - and much like dogs, they can be trained accordingly to detect various materials, including drugs and explosives. Unlike dogs, however, bees can be trained in hours; dogs take months in comparison. On the other hand, the usage of bees is limited to mere days before they are released back into the wild - in other words, using bees is the cheaper, temporary, and expedited option for detection of these substances.

Of course, lacking clearance for illicit substances, this system will be tested via (if permitted) a small dosage of Trinitrotoluene - also known as TNT. The bees will be carefully trained with pavlovian responses, with the taste of food being associated with the respective organic chemicals within the liquid explosive and teaching the bees that the representative scent equates to food, hence their proboscises sticking out when presented with said scent. This particular portion of the project would not be possible without the assistance from Dr. Patrick Bohlen, the Arboretum faculty liaison.

Once their training is complete, the bees will then be inserted into a bee-friendly cartridge and be primed to detect airflow brought in via controlled fans at the push of a button. From the moment the button is pressed, the fans will spin and the systems will begin detection, scanning for visual and infrared changes brought about by the bees extending their proboscises. For each of the two systems, independent checks will be made - one for each bee - effectively accounting for each bee being checked twice as to whether or not they put their proboscises out. Following this, the respective systems are capable of confirming each other's detection via informing the operator through LED lights. With this, we can obtain reliable and consistent results of the bees detecting the chemicals used to make explosives - in this case, the TNT.

2. Project Description and Background

The earliest use of 'sniffer' animals in a police or military setting stems back to the late 1800s, where the London police made rigorous use of bloodhounds to hunt for Jack the Ripper. Bloodhounds were already well known for their tracking abilities, though it primarily saw use in hunting animals to shoot, not hunting human beings. Soon after, however, these sniffer dogs became widely used across Europe by the constabulary to assist in finding the perpetrator for certain crimes.

Their use in explosive detection was, in truth, sparse until the start of world war two, which is when mine-detecting dogs started to emerge. Due to the decreasing metal content in the planted mines, it made metal detectors wholly unreliable - as such, carefully trained dogs quickly stepped up to the plate, becoming the Royal Engineers Dog Platoons in time for Operation Overlord, also known as the Battle of Normandy. From here on, various sniffer animals prop up for bomb detection across both Europe and the United States in both military and police positions - though both tended to keep to dogs.

Following the second world war, there was another spike in the usage of sniffer dogs - namely, the war on drugs across the United States. The noses of these dogs were trained to identify the scent of various narcotics - such as cocaine, heroin, and weed - which were being funneled into the country. These K9s proved to be instrumental in finding hidden drugs in cars, planes, boats, buildings, airports, and more. At the same time, bomb sniffing dogs became further mainstream following the 1972 Munich Olympics Massacre, a serious bombing that occurred in Munich, Germany during the 1972 Olympic Games.

The usage of explosive and drug-detecting animals has continued since then, as technologies to replace the animals have still been slow or costly. This doesn't mean that testing different animals for the same task hasn't happened; various rodents have been trained to sniff for mines given their lightweight bodies don't set them off. And in 2006, the Los Alamos National Laboratory conducted research on the topic of detecting bombs using bees. Researchers found great success in using bees to detect bombs because of their excellent sensors found at the end of their antennae. Using trained bees researchers and scientists were able to create a portable device that safely housed the bees, so they can be monitored.

2.2. Motivation

Our group decided on this project for a myriad of reasons. First, we recognized the need for an improved drug detection system. The training of drug detection dogs is expensive, time consuming, and often impractical. When states began to legalize marijuana, many dogs who were trained to detect it had to be retired. Since it takes at least six weeks to train a dog, along with a time-consuming practice of narrowing down candidates in puppyhood, this posed a significant issue. Scientists decided to turn to the advanced scent capabilities bees possessed and were able to train them in approximately four hours. As different substances are decriminalized, such as psychedelics in Colorado, our group recognized that current dogs may once again become obsolete and aim to improve the efficacy of detection bees.

The second reason is cost. While a dog needs extended training and premium foods, thousands of bees can be fed with just a pound of sugar water. Bees also do not require the cost of a dog handler. Our group saw this as an opportunity to lower the overall cost of security operations. We also saw an opportunity to increase the portability of security systems. A handheld detector is inconspicuous, easy to reload, and can be easily transported. The bees are harnessed into cartridges, meaning they can be moved without risk of the operator being stung.

The last reason we chose this project is its overall potential. Insects are highly specialized creatures with incredible sensitivity to their environment. We saw a chance to integrate what evolution has already provided with the rapidly developing technology of the optics world. We hope to demonstrate the ability of bees as useful tools, and inspire the creation of similar projects.

2.3. Goals and Objectives

The overall goal of this project is to create a handheld portable device used to monitor trained bees for bomb detection. The device will be user-friendly and easily accessible given the user has access to trained bees. The prototype device should help decrease overall cost and time in bomb detection.

As for the basic goal for this project, the absolute minimum for considering this project as a success, we are intending to have the bees detect a singular material - in this case, Trinitrotoluene - within about half a meter and be detected with an average of eighty percent accuracy for the high-accuracy camera system. The critical objectives to accomplishing this include the training of the bees, considerations regarding both the optical systems and the airflow, and the internal sensors and camera successfully catching the bees' reactions.

Advanced goals for this project include having system accuracy of eighty-five percent or higher, alongside remaining cheaper than a high-end Photoionization Detector - which go for around a thousand dollars. Additionally, the camera system should be capable of detecting within a minute's time, and the photodetector system within ten seconds of system activation. Objectives which aid in accomplishing this includes determining the best ratio of resolution to speed and accuracy for the camera system, software optimizations to further speed up object detection, and considering use of existing materials we already own and do not use - such as high-end batteries for equipment no longer purposed - instead of simply purchasing products directly from online or physical stores.

Stretch goals that we can hope to achieve in this project include a more advanced LCD display, accuracy statistical sheets that can be exported for purposes of research and overall efficacy, an accuracy of ninety percent or higher, and a cost below five hundred dollars. This would require objectives we will find difficulties following through on, such as extreme price-cutting when it comes to part procurement.

2.4. Requirements and Specifications

To help achieve our goals and objectives that we have set for this project, it would help to state the requirements and specifications therein. The requirements and specifications are the details and needs that must be met for our project design to operate successfully. In this section we will go over some of the design specifications, software specifications, and engineering requirements for this device to function properly. The design portion will cover each of the critical physical components, their respective compositions, and any critical design constraints. The software portion will cover much of the same, but with a focus on digital components instead of physical ones. The engineering requirements will cover the technical needs that the device must have to operate.

The image below shows our initial design specifications for the device. The device will include an area to store the battery, two chambers to monitor the bees, a fan system, an area to mount the PCB, and an area at the top of the device for response output. One chamber will include a camera and lens system, while the other chamber will utilize sensors. In addition, the whole device will have a fan system with pathways for the air to flow through. Starting at the nozzle of the device, the air will flow through to each chamber and out the end of the device. To help with the airflow a fan will be placed towards the tip of the nozzle as demonstrated below.

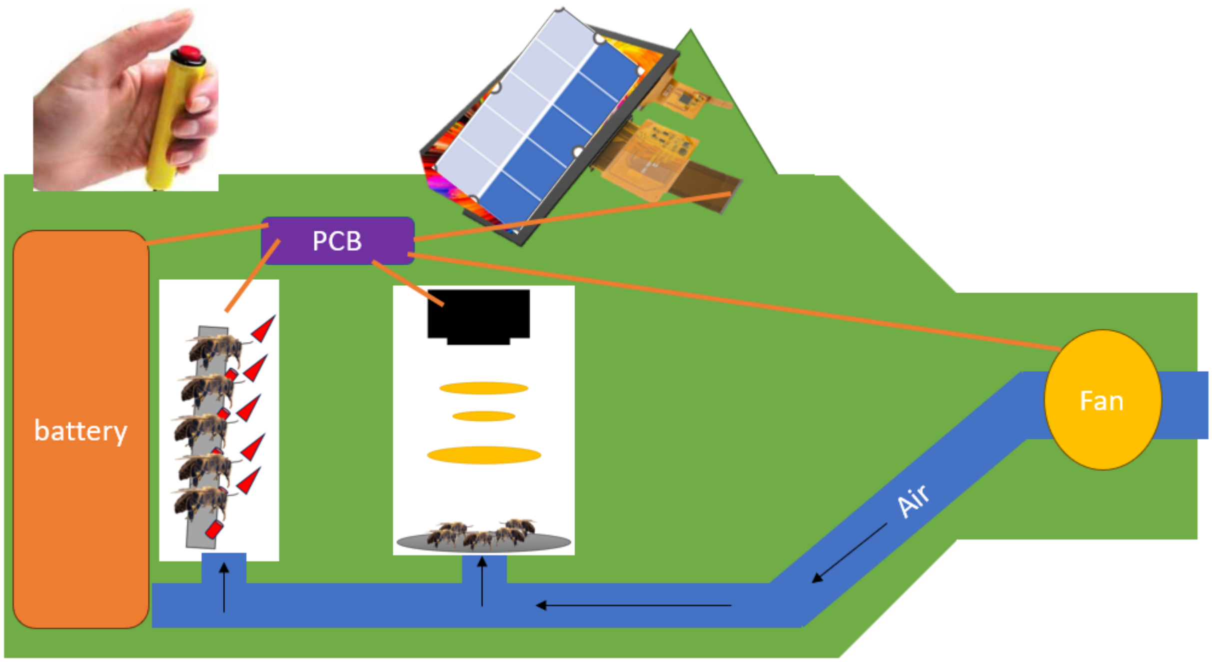

Figure 2.4.1: Rough diagram of the BEESTING device.

2.4.1. Overall Functionality Requirements

The imaging software itself will be operating either via the Region-Based Convolutional Neural Network (R-CNN) - which is an accuracy focused object detection machine learning algorithm - or via the You Only Look Once (YOLO) algorithm - which is a speed focused alternative for the same. Regardless of the selection, the end option should automate the recording process, taking around 30 or so images in the span of a second, which are then processed over the course of a few dozen seconds. From this, the algorithm selected should manage a reasonably consistent accuracy of checking for proboscis extension per bee and send the appropriate results over to the microcontroller, which will then light the appropriate LEDs on the device and output a response to the LCD. They will utilize computer vision, region proposal, feature extractor, and classifier features of the algorithm selected in order to help accelerate the process. A possible additional specification is checking for all five proboscises simultaneously, as a means to notably increase processing speed.

For the explosive material detecting device, we're looking for a reasonable list of engineering requirements to obtain consistent and reliable functionality, as seen in Table 2.4.1.1. Of course, putting aside these individual objectives, we're also looking to build the explosive material detecting device with a fairly high degree of accuracy - in this case, accuracy of measuring the response of the bees, not accuracy of the bees themselves. We're also looking to accommodate with a relatively quick response time - which also means a high quality camera. Unfortunately, this means a high likelihood of a high power requirement and a fairly high cost in order to achieve such a desired outcome. The house of quality, Figure 2.4.1.2, shows this clearly. Some more requirements involve the size and weight of the device. The device must be compact and lightweight to accommodate many individuals.

Overall Device Requirements	
Response Time	< 1 Minute [Visual Spectrum] < 5 Seconds [Infrared Spectrum]
Battery Life	> 30 Minutes
Weight	< 15lb
Accuracy	≥ 80% [Visual Spectrum] ≥ 60% [Infrared Spectrum]
Device Communication	Screen, LEDs, USB
Device Dimensions	30” x 6” x 12”
Power	≤ 40W
Bee Chambers	2

Table 2.4.1.1: Overall Device Requirements.

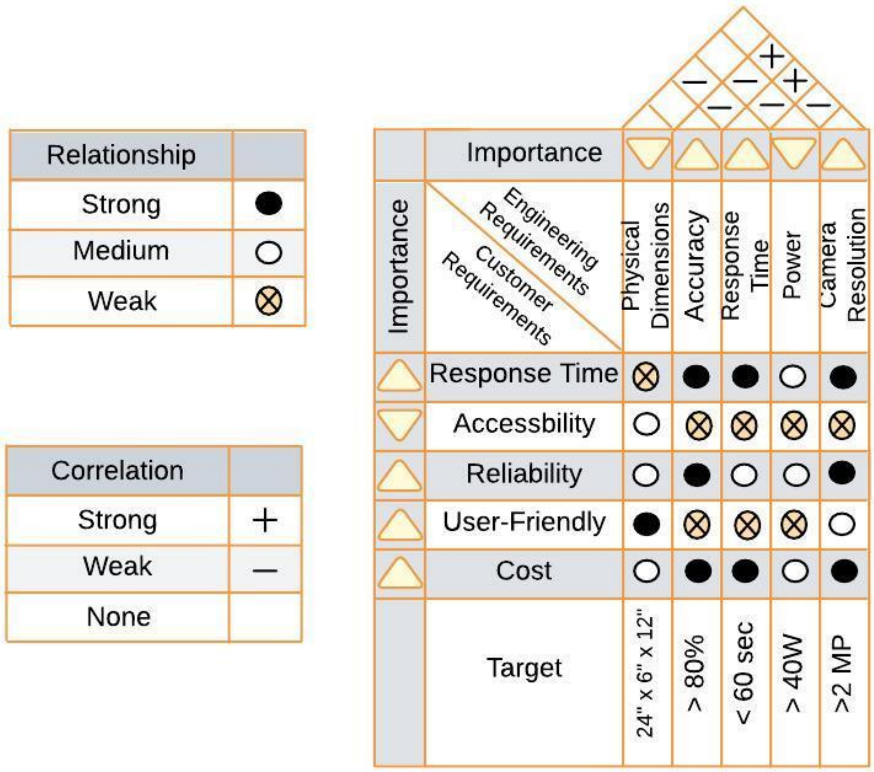

Figure 2.4.1.2: House of Quality diagram portraying relationship and correlation between engineering requirements and customer requirements.

The house of quality diagram shown above, Figure 2.4.1.2, portrays the engineering and marketing/customer requirements for the project. With this diagram one can easily understand the priorities and tradeoffs of each requirement. The house of quality also shows the correlation for all the engineering requirements.

To start, the engineering requirements for this project involve: the size, accuracy, response time, power, and camera quality of the prototype. The prototype needs to be handheld and portable, while also correctly identifying substances eighty percent of the time within sixty seconds. The accuracy, response time, and camera quality is going to receive more attention. Moving on to the customer requirements, these requirements are: accuracy, accessibility, reliability, user-friendly interface, and cost. In terms of importance more customers are going to be observing the cost, reliability, and response time of the device.

2.5. Block Diagrams

The various work for this project will be split according to the respective majors of our team. Cole Correa and Trevor Van Baulen are both computer engineers, who will primarily focus on determining and teaching the machine learning algorithm alongside the coding that will be put into the microcontroller for the fan and LED control. As both Nicholas Johnson and Hussein Shelleh are photonic scientists and engineers, they will be responsible for the development of both of the optical systems that will be emplaced into the BEESTING device. Finally, Hussein Shelleh - the sole electrical engineer of the team -will be responsible for wiring and fitting the microcontroller, power supply, switch, and fan system into the framework. To further demonstrate the workload for each member figure 2.5.1, 2.5.2 and 2.5.3 is given below. These block diagrams are split into three sections. Figure 2.5.1 portrays broad areas of the overall device. The figure 2.5.2 covers the hardware of the device and section 2.5.3 covers the software of the device. .

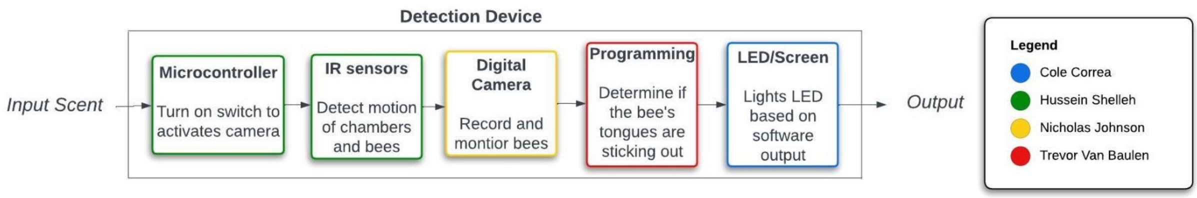

Figure 2.5.1: A pathway representing the group's individual roles and device 'action path'.

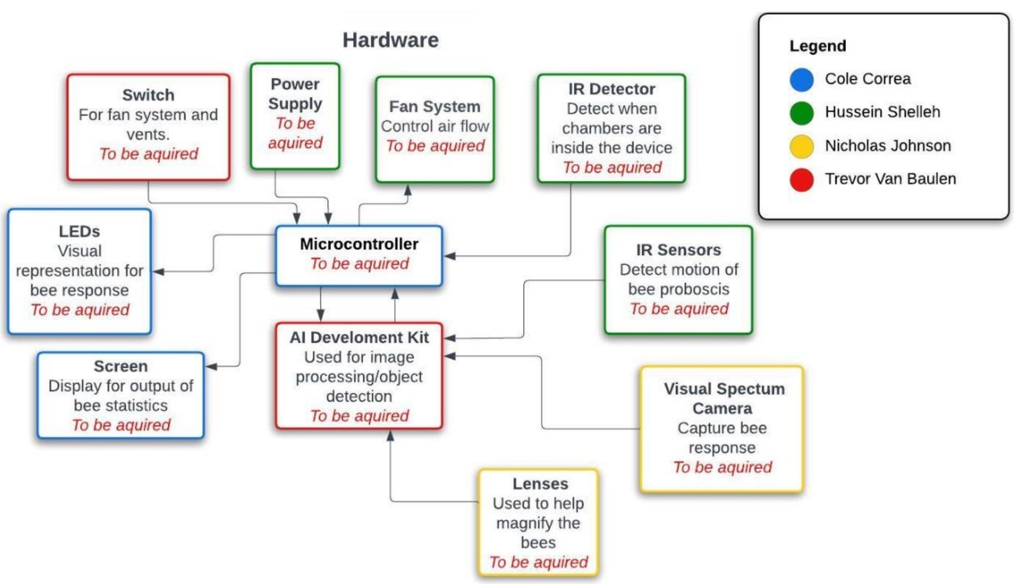

Figure 2.5.2: Hardware diagram with group's divided workload.

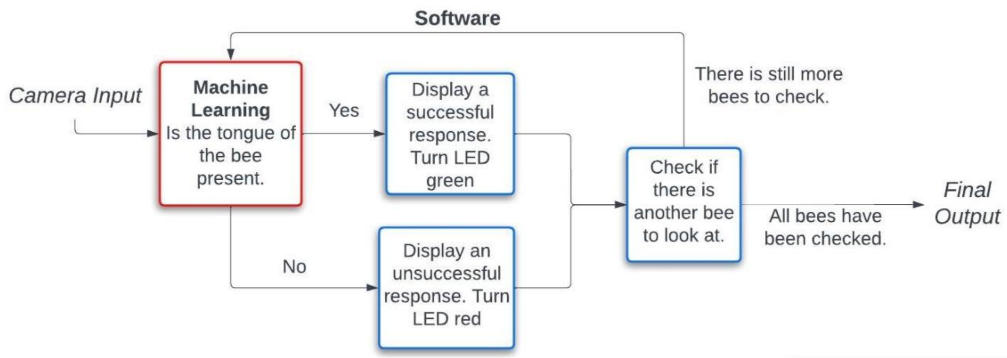

Figure 2.5.3: Software diagram with group's divided workload.

3. Related Project Research

The utilization of technologies for identifying dangerous or illicit chemical compounds has a notable history behind it, as does the utilization of variable-scale machine learning algorithms for identification of objects or triggers. These technologies are available as both commercial products or as part of developing research. Taking a deeper look at these technologies is the best way for us to find where the BEESTING may exceed or where it may falter.

3.1. Sniffer Tools and Technology

The primary baseline of BEESTING is the capability to detect organic chemical components used in explosives, and for the sake of the proof of concept, specifically liquid TNT. The process is accomplished by 'feeding' the housed bees air that may have trace components of the compound and watching to see if they react accordingly. In the case that they do, then the target object most likely has the liquid TNT within it. However, understanding the related technologies for detecting compounds - both on similar and broader scales - is critical to showing where these bees may be a better or worse fit.

3.1.1. Detection Dogs

Detection dogs are by far the best known example of research for finding numerous types of explosive, poison, or narcotic. Various shows and films covered and subsequently popularized their use both within the context of detecting low-metal mines in war and within the context of detecting a multitude of substances in daily police or security work [1]. For the context of our research, we primarily focused on the latter.

Law enforcement uses several dog breeds within their forces based on region, both small and large, and trains the dogs to first operate as proper police dogs. The process takes several years and requires significant effort from both the handler and the dog. This can be compared to finishing high school prior to entering college for further specialization. Following this, these police dogs can then branch out into different specializations based on the need of the specific department, the availability of training, and the breed of dog. For detection dogs specifically, there are one of four options: cadaver searches, explosive detection, narcotics detection, or search and rescue operations.

Figure 3.1.1.1: A Sapper from the State Emergency Service of Ukraine clearing Chernihiv Oblast of ammunition that did not explode, with assistance of a detection dog.

In the United States, these detection dog units are commonly deployed alongside police and government security for the sake of checking those pulled over, those at the border, and those travelling on certain boats. Airlines can also include detection dogs, but they've been mostly phased out in recent decades due to the use of airport scanners and other technologies. These dogs then make use of their powerful noses and training in order to detect the selection of compounds they were taught to identify.

The total cost for preparing a detection dog, from start to end, is approximately four years of effort and over twenty thousand dollars in upfront requirements. This does not factor in additional costs such as animal veterinary care, professional diet regimens, nor any post-service costs such as a pension [2]. In turn for these extensive costs, detection dogs typically operate in service for somewhere between six to nine years on average. Detection dogs are capable of detecting both organic and inorganic arson accelerants, drugs, and explosive compounds. Further specialized detection dogs are capable of finding cadavers, currencies, digital technology [3], specific agricultural products, and viruses, among other things. Dogs can additionally identify multiple compounds at once, albeit with additional training and different diet specifications.

Despite their size, the incredible detection ability of these dogs is something to be marveled at; a dog's olfactory sensors are capable of detecting scents at the scale of one part per trillion, something modern technology is only beginning to reach. The bees which we will be using have slightly stronger olfactory sensors, which is negligible at this scale. However, what we will be unable to reproduce is the extended lifetime of ‘work’, the distinct, easy-to-read tells of a dog, or their ability to sense multiple compounds.

3.1.2. APOPO HeroRATs

The Anti-Persoonsmijnen Ontmijnende Product Ontwikkeling (APOPO), which translates to “Anti-Personnel Landmines Detection Product Development”, is a joint Belgian non-governmental organization and United States non-profit organization that has come together to train a multitude of southern giant pouched rats (*Cricetomys ansorgei*) in the detection of landmines [4].

Founded in Belgium in the year 1997, APOPO started as a personal project for Bart Weetjens and Christophe Cox after discussion with Professor Ron Verhagen of the University of Antwerp, said university’s rodent expert in the department of evolutionary biology. Through further collaboration with the Sokoine University of Agriculture in Morogoro, Tanzania, they managed to requisition several Gambian pouched rats and began their work. With Belgium’s foreign aid funds helping their research, APOPO did what it could before it formed a partnership with the Tanzanian People's Defence Force in the year 2000.

Figure 3.1.2.1: Bosco the HeroRAT, a landmine-sniffing rat at the APOPO Visitor's Center in Siem Reap, Cambodia.

The first trained rats were accredited in 2004 according to the International Mine Action Standards, and in the following years this first ‘class’ and more began their work across Africa [5]. From Mozambique, to the Gaza Province, to the Maputo, Manica, Sofaka and Tete Provinces and even Angola and Cambodia, APOPO assisted in clearing out a vast majority of the remaining mines across the regions. The landmine-sniffing rats were incredibly pivotal for these regions, due to being lightweight enough to not set off the mines and keep everyone as safe as possible during the effort.

APOPO's training of these rats takes around nine months - though this does not include the medical checks or the final set of tests the rats must take - and costs, on average, six thousand euros, or around six thousand, five hundred, and seventy-seven United States dollars. APOPO breeds and raises the rats themselves, starting training at just four weeks old. At first, the young rodents are familiarized with various human elements, then they are slowly trained through pavlovian response until they can identify the location of dummy minds while blinded. If they fail their final examinations, the rats are preemptively retired to enjoy the rest of their lives without doing a thing. The southern giant pouched rats that complete training and are permitted to work in a live setting work for four to five years before they're retired much the same.

These animals are trained for various emplaced explosives, but they require time to fully acclimate when they enter sufficiently different regions in order to operate effectively. However, the rats also require a significant amount of hands-on assistance for actual operation [6]. Metal detectors still find themselves used alongside them, same with tools to trim areas with foliage too heavy for the rats to search through. Additionally, mice have noticeably weaker olfactory sensors, operating at a scale of a tenth of a part per million. The speed at which they operate significantly counteracts these drawbacks, as does the fact that Africa is their natural environment. Unfortunately, this advantage is lost for the purpose of BEESTING.

3.1.3. Photoionization Detection Sensors

Photoionization Detection Sensors, or Photoionization Detectors (PIDs) are gas detecting tools that primarily focus on the detection of volatile organic chemical compounds. PIDs can specifically detect the concentration of these airborne compounds via use of an Ultraviolet (UV) light source, which is used to ionize compounds with a similar or lower energy threshold and break them down into both electrons and positively charged ions. The energy spent ionizing the particulates is carefully measured with a connected ammeter, as chemical compounds have specific thresholds - or Ionization Potential (IP) value. If the ammeter reads the target value, then it identifies that the air has particulates of the target compound. With these techniques, one can detect chemical compounds from between a tenth of a part per billion to ten thousand parts per million - it matters the specific device in use and compound targeted [7].

These PIDs are capable of an incredibly broad potential range for compound detection, including acrylates, alcohols, aldehydes, alkanes, alkenes, aromatics, bromides, esters, ethers, iodides, ketones, mercaptans, organic amines, and even several inorganic compounds. However, despite this truly extensive range of options, until recently a vast majority of PIDs were built with a mere current reader and a separate table to identify the probable compounds. More recently, PIDs are built in one of two ways. The first is for a PID to specifically target a singular chemical compound and its close chemical relatives, which limited the particular targeting range of the device but resulted in it being fairly small and cheap - usually under one thousand dollars - with some variants of the device having the ability to change the target range via purchasing additional filters. The second has an electronic display and a notably larger set of compounds which it can check at once, but it is considerably more expensive than its small-range counterparts; larger-range PIDs can cost up to ten thousand dollars based on the company and compounds selected.

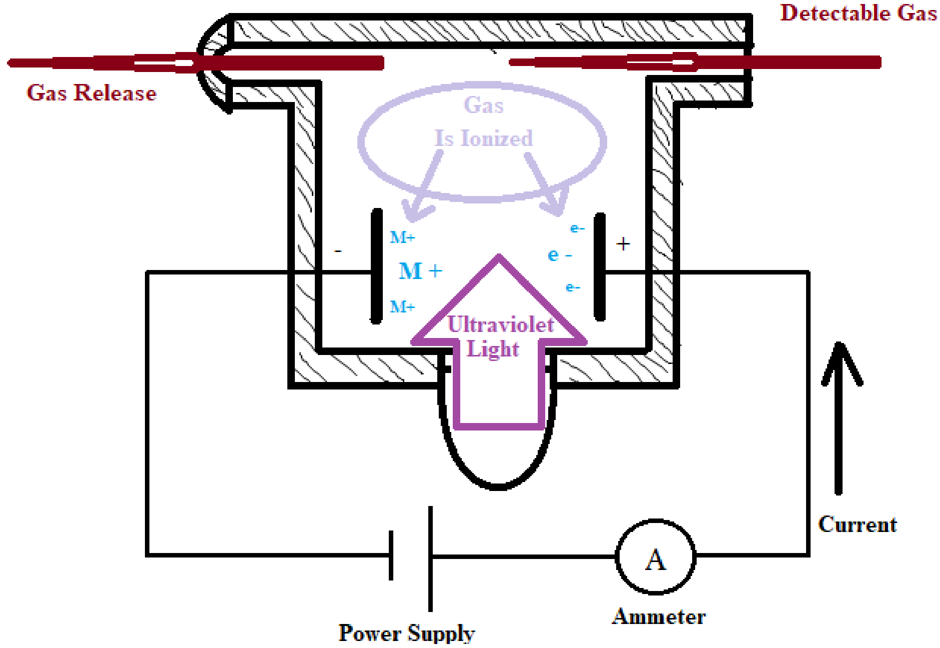

Figure 3.1.3.1: An MSPaint diagram of how a simple PID operates.

In comparison to bees, these PIDs can detect a larger overall range of compounds, as they have the capability to detect a small amount of inorganic chemical compounds. Additionally, PIDs can identify a range of compounds at once, where bees can only detect one trained compound. Third, these devices are highly robust and reliable once properly calibrated, and can be used in environments where bees cannot. Versus all of these advantages, the bees have a higher range of detection when let loose, and can detect significantly smaller concentrations - in the range of parts per trillion - versus PIDs.

3.1.4. Gas Chromatography–Mass Spectrometry Machines

Gas Chromatography-Mass Spectrometry (GC-MS) is a highly advanced process which combines the key features of two chemical analysis processes brought together to form a comprehensive identification process of a multitude of substances within a target sample. The two processes, as the name suggests, are Gas Chromatography and Mass Spectrometry. This dual-feature combined result has become a modern standard in criminal forensics, environmental analysis, chemical engineering, food and drink analysis, perfume and cologne analysis, astrochemistry, and more. To say that the result is greater than the sum of its parts would not be an inaccurate statement. However, understanding these parts is still critical to understanding the final process.

Gas Chromatography (GC), also known as Vapor-Phase Chromatography (VPC) or Gas-Liquid Partition Chromatography (GLPC) is the chemical process of separating and analyzing compounds that can be vaporized without making use of any kind of decomposition. This is accomplished by injecting a gas or liquid sample into an inert or unreactive gas - known as the mobile phase - which then is moved along a narrow tube. This tube, colloquially called the column of a gas chromatograph, moves the sample with a continuous flow while being heated within an oven. The materials which make up the tube lining and filling - called the stationary phase - works in tandem with the heat to filter through the sample and break apart its individual components, which are finally ejected and observed electronically [8].

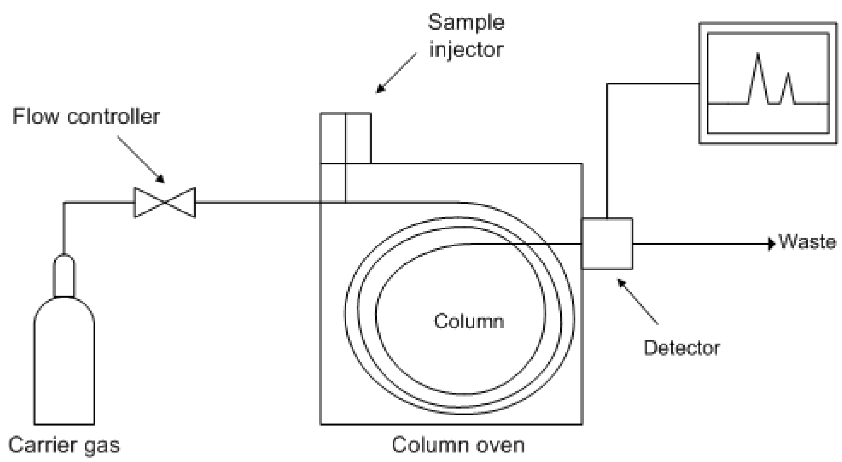

Figure 3.1.4.1: Diagram of a Gas Chromatograph.

Mass Spectrometry (MS) is a process that's been used for over a century, invented in the year 1918 by Arthur Jefferey Dempster following advancements with cathode and canal ray tubes. It's an analytical process which is used to measure the mass to electric charge ratio of ions, which are then plotted along a mass spectrum (an intensity plot for mass to electric charge ratio). This mass spectrum plot is then used to determine the elemental signature, isotopic signature, mass of particles, and in the case of a complex sample, the possible chemical identity or structure of the target sample. The primary components of a mass spectrometer are an ion source, a detector, and a mass analyzer. The ion source converts a portion of the test sample into ions, which are then removed from the rest of the sample and run through both the mass analyzer and the detector. The separated ionized sample is separated into fragments that are then sorted by their mass to charge ratio, which the detector reads through to provide the resulting abundance data.

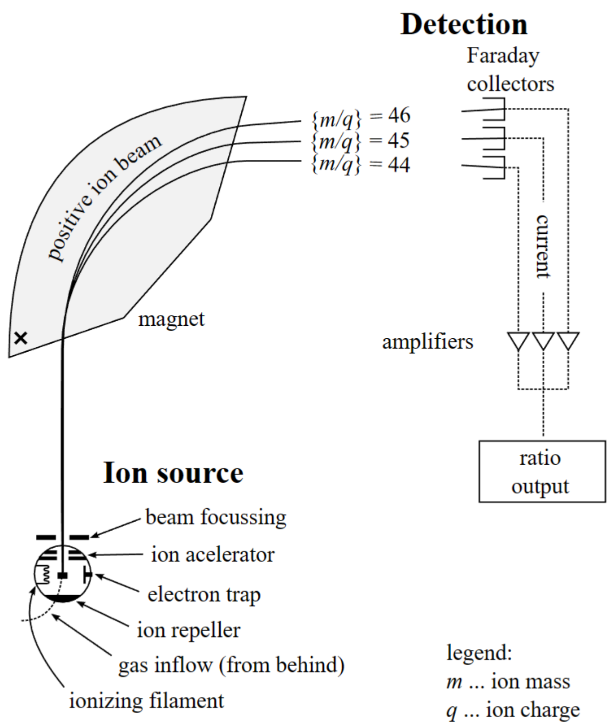

Figure 3.1.4.2: Diagram of a simple Mass Spectrometer. The example values are in reference to reading Carbon Dioxide isotope ratios.

These two machines come together to form the Gas Chromatography–Mass Spectrometer. In short, this combined design operates by having the mass spectrometer handle the sample following the electronic detection and observation suite. The combined data results in a comprehensive suite of information for the user, which is highly detailed and capable of reading an extensive range of materials, both organic and inorganic [9]. However, the concentration requirements for these machines are difficult to discern. Additionally, operating these machines takes experience, and normally requires a laboratory setting. This is not including the impressive price that the machines fetch - tens of thousands of dollars on the low end alone.

3.1.5. Explosive Trace Detectors

Explosive Trace Detectors (ETDs) are a type of detector that can find trace particles in the air. The most commonplace form of these are chemical colorimetric kits, which change color when rubbed against a sample to check for trace amounts of the compound. However, these are highly limited and one-time use. It's far from the only form of ETD, as there are other disposable and in-research methods, such as chemiluminescence and thermo redox. Among these options, there is a known and reliable process called Ion Mobility Spectrometry (IMS). This process has certain variations, such as Ion Trap Mobility Spectrometry (ITMS) and Non-Linear Dependence on Ion Mobility (NLDM) built on the same principle [10].

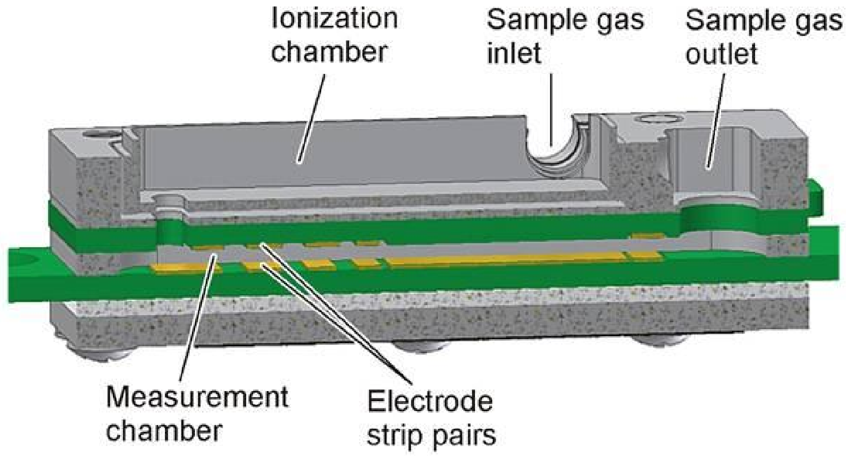

Figure 3.1.5.1: An Aspiration-Type Ion Mobility Spectrometry sensor.

IMS is an analytical research method that searches and identifies the presence of ionized target particles via observing the mobility of a carrier gas. The sample air is pulled into the detector, where it is ionized while in motion. The then-ionized air is measured via a perpendicular electric field, with said field capable of being static or variable. With this data, identification can be made following similar principles to Mass Spectrometry - by paying attention to the mobility of the particles, mass can be calculated and enough information can be gleaned to determine what compounds are in the sample with high accuracy.

Not only is this process fairly ingenious, it is also one that's able to be mobilized and carried around for easy on-site detection versus GC-MS. However, the consequences of this are that IMS is insufficient for handling inorganic compounds, and that it's nearly half the lower-end cost of a Gas Chromatography-Mass Spectrometer as is. Additionally, most types of these devices traditionally aren't sold to just about anyone, as their primary use is military and security.

3.1.6. Comparison

This project's primary focus is on the creation of a cheap alternative to explosive and/or narcotic detection technology. In other words, two most critical components for something like this would be the time it takes to train a user (and an animal), the cost of teaching or maintaining this animal, and the effective capabilities of the chosen technology.

Bees, as our chosen technology, require minimal time to train and prepare given the company in question has access to bees and a lab to work with. Bees have an incredible sense of smell, and given most explosives and all narcotics contain chemically organic compounds, it covers a vast majority of hypothetical dangers. However, these bees come with a highly unfortunate drawback: they can only be each trained to target a singular chemical. Similarly to a single-target PID, the 'batches' of bees would have to be individually tuned for specific compounds. This can be notably impractical in a setting like an airport, but it has its uses when it comes to narrowing down what to search for with other technologies.

	Bees	Dogs	Mice	PID (single)	PID (multi)	GC-MS	EDT
Training Time	< 8 Hours	~5 Years	~9 Months	None	None	N/A	None
Preparation Time	< 1 Minute	< 1 Minute	< 1 Minute	< 1 Minute	< 1 Minute	< 10 Minutes	< 1 Minute
Detection Time	Seconds	Seconds	Seconds	Instant	Instant	5 - 30 Minutes	~1 Minute
Operational Lifetime	4 - 5 Days	6 - 9 Years	4 - 5 Years	Near-Indefinitely	Near-Indefinitely	Near-Indefinitely	Near-Indefinitely
Mobile?	Yes	Yes	Yes	Yes	Yes	No	Sometimes
Inorganics?	No	Yes	Sometimes	Sometimes	Sometimes	Yes	No
Compound Range	Single Target	Multiple Targets	Single Target	Very Small Range of Targets	Small Range of Targets	Extreme Range of Targets	Large Range of Targets
Concentration Range	Parts per Trillion	Parts per Trillion	0.1 Part per Million	0.1 Part per Billion - 10k Parts per Million	0.1 Part per Billion - 10k Parts per Million	N/A	Parts per Trillion
Cost	Bees and a Lab	> $30,000	> $6,600	≤ $1,000	≤ $10,000	> $60,000	> $25,000

Figure 3.1.6.1: Table of Technological Options for 'Sniffer' Devices.

3.2. Optical Components

The BEESTING device will be operating on two different optical systems. These systems will each represent different critical components to the functionality of this project, and through them we intend to deliver both speed and accuracy to the user.

The system critical for accuracy uses a visual spectrum optical lens design, which is interconnected with a camera and a machine-learning algorithm. Through this system, we can achieve a high accuracy on detecting if the bee proboscises have extended or not, and therefore accurately determine if the bees successfully detect the target compound. However, due to the process involved and the multiple steps necessary to achieve the final result, this process is slower than what one desires in a tense, time-sensitive situation. As such, the speed-oriented optical system consists of infrared wavelength detection technology without any additional metaphorical ‘hoops’ to jump through, immediately sending the necessary electronic signals through the device to the final displays and giving the user of the device a response in seconds. However, the tradeback for using such a high-speed system is the risk of inaccuracies due to the risk of false activations.

Combined, these two systems form an early response and delayed affirmation, effectively giving the system two points of possible confirmation that work in tandem to deliver consistent particulate detection.

3.2.1. Optical Lens Materials

The visual spectrum optical design will be, by virtue of its location near the bees, subject to no small amount of particulates and small-scale wear and tear. Additionally, due to the inherent size of the BEESTING device, this optical system is additionally required to be notably compact in size. We also must consider the necessities of image clarity and resolution for the machine-learning algorithm, as poor image quality or too high a resolution will risk a significant increase of runtime for the code in question.

First and foremost is the operational range of wavelength the requisite lenses function under. All options considered must be within the visible spectrum. Following that is assuring the necessary clarity - the surface clarity and Abbe Number. Surface clarity is self explanatory, and a material’s Abbe Number is a measure of chromatic aberration, color fringing, and wavelength-index dispersion; the higher the Abbe Number, the lower these values are and the higher inherent clarity of the image is. A low Abbe Number will result in color-distorted and warped images, and a low surface clarity will simply result in poorer images in general.

What is equally critical in this scenario is durability. Lenses can have clarity issues when it comes to certain particulates or environments - such as the possibility of using the BEESTING device in areas with large concentrations of dust. This additionally damages the surface of the lens, as do other environmental conditions like thermal shift and shock. The latter two are especially worrisome for a device operating with a handheld power supply, which tends to heat up. Therefore, there are four important factors to consider: Density, Young's Modulus, Shear Modulus, and the Coefficient of Thermal Expansion. It is desirable for the lens to possess a high Density, Young's Modulus, and Shear Modulus, but a low Coefficient of Thermal Expansion (too high a coefficient risks damage to the lens from being unable to expand and contract from heat and cold).

Finally, there's a need for the lenses to be both affordable and accessible. Optical components like lenses usually cannot be purchased in traditional stores and tend to be fairly expensive - even when it comes to poorer qualities. Therefore, making sure the target material's usual pricing isn't obscene is a critical factor for our selection.

These combined considerations led us to pick from three different lens materials: Fused Silica [11], N-BK7 [11], and N-LASFN9 [12][13]. All three fit to some extent within our various desired factors - some more than others - and have their inherent advantages and disadvantages. Following that, we chose the option which best suited our needs and our budget, and selected the N-BK7 as our material.

Name	Fused Silica	N-BK7	N-LASFN9
Wavelength Range	195-2100 nm	380-2100 nm	380-2500 nm
Index of Refraction	1.46019	1.51886	1.8
Surface Quality	20-10	40-20	40-20
Abbe Number	67.4	64.17	32.20
Density	2.51	2.51	4.44
Young's Modulus (GPa)	73	81.5	104.6
Shear Modulus (GPa)	31	34	40
Coefficient of Thermal Expansion	0.52	7.1	7.4
Relative Cost	Low	Low	High

Table 3.2.1.1: Comparison of Optical Lens Materials.

3.2.2. Broad Bandpass Filters

The primary objective of the Visual Spectrum imaging system is to simply image the bees proboscises at such a resolution and clarity that once it's done recording, all of that visual data can be passed to the AI Development Board to then process it as quickly as possible. This makes the job of the Lens System fairly rudimentary and straightforward, leaving the bulk of the work to the AI Development Board and the Machine Learning Algorithm to compile and process the information given. This can take an extremely long amount of time for the nature of the product, especially since we're sending the data as whole videos and not individual images. To get around this we hope to implement a Bandpass Filter.

A Broad Bandpass Filter is an optical window that is used to alter or change the incoming light into the system. The Broad Bandpass Filter does this by taking extremely small amounts of materials that have exceptionally high levels of absorption for specific Wavelengths, and adding those materials into the mixture of the Host Glass during the manufacturing process. The result is an optical component that will let you specifically remove certain Wavelengths of light from the system via absorption, thus effectively filtering them out.

Implementing this special optical phenomena into our Visual Spectrum Imaging System will let us cut out about half of the wavelengths within the Visual Spectrum. This, in turn, will allow us to significantly increase the color contrast of the bees' proboscises relative to the rest of the chamber and cut out an equally significant amount of the data that is then transmitted and processed by the AI Development Board.

After doing a substantial amount of research on Broad Bandpass Filters and comparing them to our use and application into our system, we've found that a UHC Broad Bandpass Filter would be the best suited for the job. With that in mind, we focused our selection further and brought it down to a handful of potential Filters to choose from.

Filter Name	Size	Surface Quality of the Optical Window	Cost
Optolong UHC MAP	1.25 Inches	20 µm - 1 µm	$55.00
Astronomik UHC Filter - Round Mounted	1.25 Inches	20 µm - 1 µm	$99.95
SVBONY Telescope UHC Filter Astrophotography	1.25 Inches	60 µm - 4 µm	$28.99

Table 3.2.1: Broad Bandpass Filter Comparison.

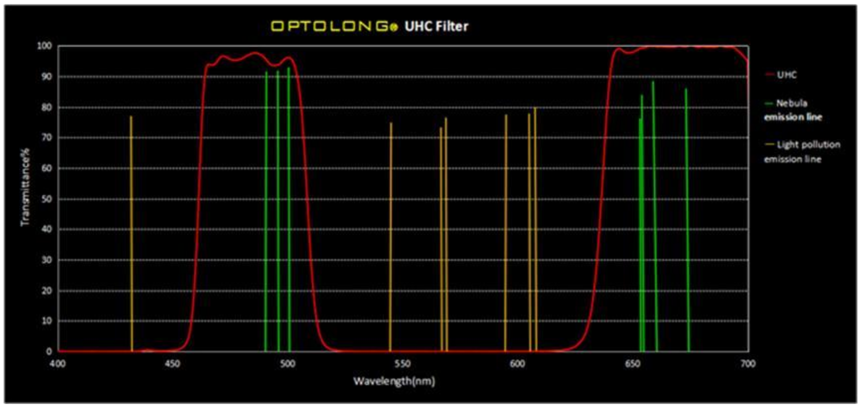

Figure 3.2.2.1: Transmission of UHC Spectrum and Characteristics of the Optolong Filter.

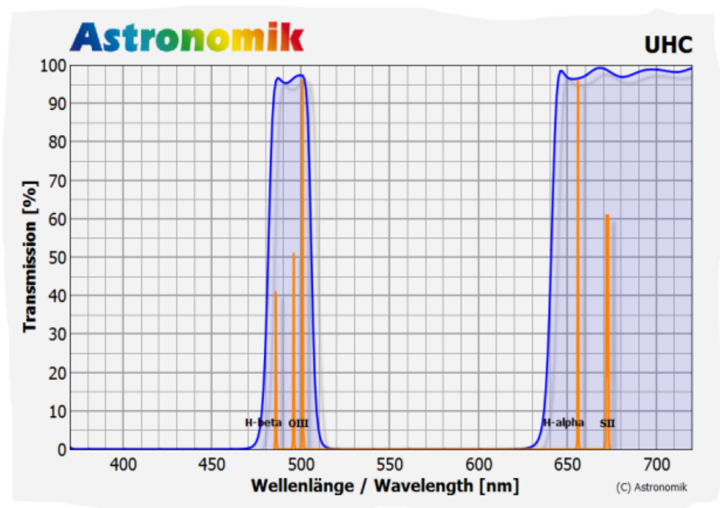

Figure 3.2.2.2: Transmission of UHC Spectrum and Characteristics of the Astronomik Filter.

First, we'll focus on the two main filters being considered - Optolong's UHC MAP and Astronomik UHC Round-Mounted Filter. Both of these filters are very promising. They both are from exceedingly reputable and reliable companies, and yet that isn't reflected in their reasonable pricing for their Filters.

Another point that is extremely important is the Surface Quality of the two Filters. Both Optolong's UHC MAP and the Astronomik UHC Round-Mounted Filter can ensure a optical quality of 20µm - 1µm, which is relatively high in the industry, while SVBONY's filters can only guarantee a 60µm - 40µm. This isn't the worst relative to what's on the market, but it's low for our purposes; poor Surface Quality can be the source of scattering and loss of Visual Quality.

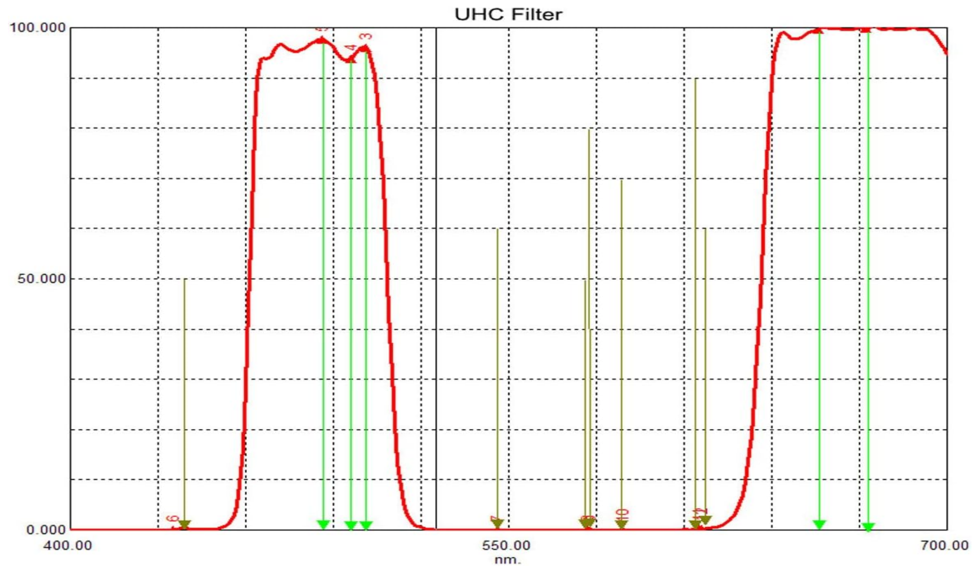

Figure 3.2.2.3: Transmission of UHC Spectrum and Characteristics of the SVBONY filter.

Lastly, Astronomik's UHC filter is optimized for use in optical systems with at least two inch aperture instruments, and performs best with five inch apertures and systems with a Focal Ratio of f/15, which is not possible based on the compact constraints of our system.

After running simulations to on all three lenses after accounting for the the optimizations of each lens and how they may positively or negatively impact the system the Optolong's UHC Global MAP was the clear winner over the other two lens when comparing how the scattering induced from the SVBONY filter would destroy the image quality and the Astronomik filter produced very close images in terms of quality but still lower based on that and the difference in terms of pricing we have chosen to go with Optolong's UHC Global MAP.

3.2.3. IR-Wavelength Detection

Alongside the visual spectrum components, the BEESTING device will be using an infrared detection process on a secondary set of bees - this is equivalent to a lower-accuracy, 'early warning' system that should tell the operator if there is a nearby risk within seconds compared to the visual spectrum system's longer but more accurate information. However, infrared systems typically have different considerations versus their visual spectrum counterparts. Most critical are the factors of observable range, peak wavelength, cost, and size. As such, the choice of detector is merely twofold: Photodetectors, and Photodiodes.

Photodetectors, sometimes called photosensors or light sensors, are sensors that can detect electromagnetic radiation. The specific applications for photodetectors tend to be fairly broad in scope, from things such as solar panels and automatic lighting, to performance responses, to photochemistry and more. One of the most commonplace uses for photodetectors is for compact disks (CDs) and Compact Disc-Read Only Memory (CD-ROM), forming the backbone of optical data storage technology.

In the case of this project, we're looking specifically at semiconductor-based photodetectors. These particular electronic components typically operate with a Positive-Negative (P-N) Junction semiconductor, which converts the emitting photons into electrical current [14]. This is accomplished via the photon energy forming electron-hole pairs in the depletion region of the P-N Junction. Certain forms of solar cell make use of this form of photodetector.

Some photodetectors are built with specific controls or data-management programs that can be used in conjunction with a desktop in order to get precise, high-quality data. These photodetectors, however, are fairly large and exceedingly expensive. Used high-quality data-measuring photodetectors go for over seven hundred dollars at the cheapest, increasing in price based on the specific operational range and the company which produced it. This is not what we want; our goal is to simply identify if there are sufficient optical emissions reaching it - this is to check if the bee's proboscis has extended. In turn, the cost, size, and complexity of the photodetectors drops dramatically. In our case, the photodetectors within infrared range cost around two dollars per detector.

Photodiodes, similarly to photodetectors, are electronic devices that detect light. However, photodiodes are built slightly differently to photodetectors. For one, some photodetectors use photodiodes as one of their requisite components - such as in CD-ROMs. For another, photodiodes usually operate with a Positive-Intrinsic-Negative (PIN) Junction semiconductor, due to PIN Junctions increasing the detection speed versus other options.

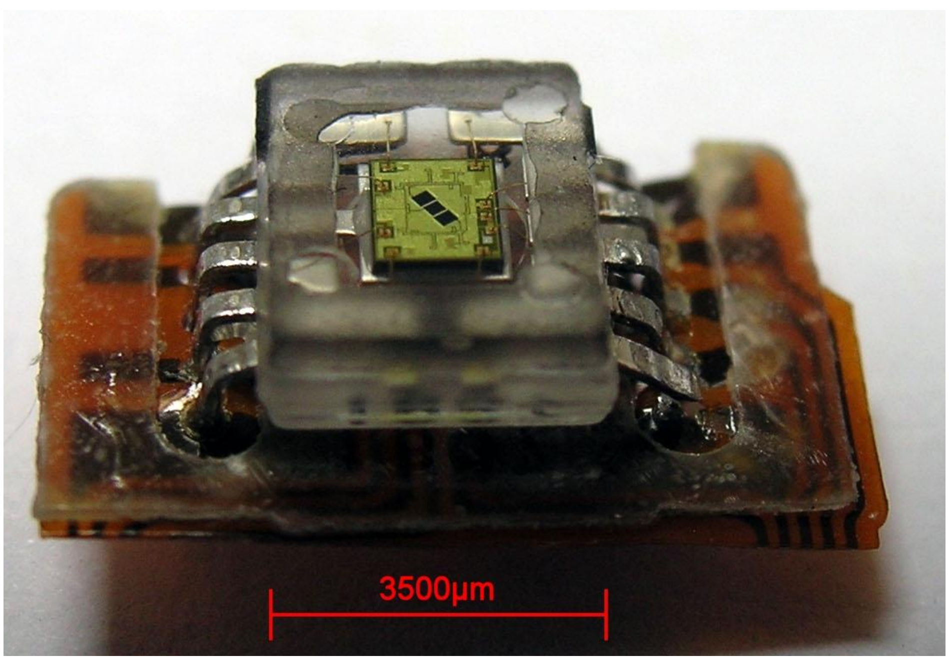

Figure 3.2.3.1: Close-up of a Photodetector salvaged from a CD-ROM. The three black squares in the center are Photodiodes.

For the sake of our project, we would be operating the photodiodes with a reverse bias in order to achieve a photoconductive state - this will allow us to 'measure' what the photodiode is observing, and through detected spikes in the circuit we can in turn mark if a bee has extended its proboscis - and mark if it detected the compound.

Component	TSSP4P38 Photodetector (Semiconductor) [15]	3DU5C Photodiode (RB) [16]	Luckylight Photodiode (RB, Filtered) [17]
Light Sensitivity	Moderate	High	High
Approximate Size	Single LED	Single LED	Single LED
Electrical Noise	Low	Moderate	Moderate
Operating Voltage	2.5-5.5V	N/A-10V	0.5-1.3V
Observable Range	Visible to IR [Specific N/A]	400-1100nm	700-1200nm
Peak Wavelength	940nm	940nm	940nm
Shipping Time	Days	One Day	Weeks
Cost	~$2 Each	~$10 per Five	~$1 per Five

Table 3.2.3.1: Comparison of a Photodetector and two Photodiodes.

After sufficient research, we selected a photodiode with the range closest to lower-infrared and with the least amount of the visual spectrum possible - all without paying excessively. It is a Luckylight LL-503PDD2E Photodiode, sized at five millimeters in diameter.

3.2.4. Camera For Object Detection

The second chamber within the device, the one operating within the visual spectrum, will utilize an AI development board in conjunction with a camera. Although the lens for the camera will be designed separately, we still need to have some considerations for what type of camera we want to implement. We initially considered using a type of web camera for inside the device, but after some discussion we eventually settled on a microscope camera or variation of the type to achieve what we needed. This is to ensure that we are able to get a proper image of the bees and have a camera small enough to fit into our device and be mounted from above within the chamber. We need the camera to produce a decent resolution and image for the object detection model to identify the bee proboscises. The camera also needs to fit within the chamber and provide enough space for both the lens and the bees to be housed within the chamber as well.

For this project, we looked at three different cameras for our device. They are the MD310C-BS from AmScope, a BoliOptics 5MP CMOS Color Digital Microscope Camera, and the AmScope 5MP Color CMOS C-Mount Microscope Camera. When looking at these three cameras we considered a few factors. They are MegaPixels (MP), size, weight, type of connection, sensor range, resolution, frames per second (FPS), and the price. Some cameras also have special features included with software that were taken into consideration. Each of these cameras' image sensors are CMOS sensors.

When comparing the cameras one of the first considerations we looked at was the MP. This is due to the fact that MP defines the quality of the image/video taken with the camera and how many pixels will make up the images and videos. More pixels equates to crisper and smoother images and videos. Being that the camera will be implemented with object detection, having a higher MP will allow for a more detailed image. That being said, we decided to go with the camera that has the lowest MP out of the three we considered. That is the MD310C-BS, which only varies by 1.9 MP from the other two cameras. Though it has slightly less MP, this does not have a massive impact on overall image quality that we should expect especially since we will also be using our own lenses.

Another important consideration was the weight and size of the camera itself. Since we want the BEESTING device to be portable and as light as possible, the weight of the camera itself can not be that much. Being that the cameras are small, the weight is not too significant but with enough small parts and components the weight can add up. Size was the other factor, which is to ensure that it can fit inside our chamber and to maintain a certain height so the camera is not closer to the lens. When looking at these two factors, the MD310C-BS is a proper size with a weight that is similar to the other cameras.

Another important aspect of the cameras we looked at was the type of connection it required. Since the camera needs to connect with the AI development board, a standard connection is needed that is readily available to the AI development boards that are discussed later on. Each of the cameras we compared utilize a USB 2.0 connection. Though most AI development boards use USB 3.0 connections, a 2.0 connection can still be utilized making each camera a viable option.

Sensor range for the cameras also needed to be compared. Since the camera will be recording the bees' proboscis, the camera needs to be focused on a small area. Even though our own lens will allow for better imaging of all the bees within the chamber, having a proper sensor range is still important for helping detect when the action we are checking for occurs. This meant considering a sensor range on a slightly larger scale but one that still allows for focusing on just the proboscis of the bees. The area covered by the MD310C-BS provides enough area while still keeping to a size that is within reason, while the Bolioptics provides only a diagonal range and the AmScope has a considerably larger sensor size then the MD310C-BS.

Resolution and the FPS of each camera was also an important consideration to make sure that the camera has sufficient frames to pass to the object detection. When the bees' proboscis extends the camera must be able to capture it within a FPS that is quick enough. If not, the imaging could miss the moment and lead to false negative readings which can be catastrophic when trying to detect illegal and dangerous materials. For our project we want a resolution that does not need to be high but can run at a FPS fast enough for the object detection model to run through and detect the images passed. When looking at each camera the MD310C-BS provides the highest FPS at all ranges of resolution meaning whichever resolution we decide, will still have the highest achievable FPS from the camera.

The last factor that was compared was the price. Since we wish to keep the price of the BEESTING device under five hundred dollars, the camera must be considered with that in mind since microscope cameras of decent quality can run for hundreds of dollars. The MP of the camera was one of the first considerations made when choosing a camera, but as the increase in MP went up so did the price. This meant having to sacrifice MP while still trying to maintain a high MP count to guarantee an image quality that is acceptable and that object detection is capable of discerning what the model is looking for.

Name	MD310C-BS (AmScope)	BoliOptics 5MP CMOS Digital Microscope Camera	AmScope 5MP Color CMOS C-Mount Microscope Camera
MegaPixels (MP)	3.1 MP	5 MP	5 MP
Size (mm)	29 x 29 x 29 mm	58 x 58 x 37 mm	Camera Dimensions not listed.
Weight	Not Listed	0.29 kg (0.64lbs)	Not Listed
Connection Type	USB 2.0	USB 2.0	USB 2.0
Sensor Range/Sensor Size/Sensor Area	5.12mm x 3.84mm	7.182mm Diagonal	5.70mm x 4.28mm
Resolution and Frames Per Second (FPS)	83 FPS @ 680x510, 43 FPS @ 1024x768, 12 FPS @ 2048x1536	60 FPS @ 640x480, 18 FPS @ 1280x960, 5 FPS @2592x1944	60 FPS @ 640x480, 18 FPS @ 1280x960, 5 FPS @ 2592x1944
Price	$169.99	$284.98	$200.99

Table 3.2.4.1: Visual Spectrum System Camera Comparison.

3.3. Visual Representation Components

This section will go into depth on some of the considerations into the project's visual representation components. The visual representation components will cover the light-emitting diodes (LED) and liquid crystal displays (LCD). Like in any project, these components will provide the user with a visual aid to the response of the system. Therefore, these visual components must satisfy certain requirements. Each subsection will discuss the considerations, comparison, and selection of each part.

3.3.1. LEDs

The three choices for the LEDs of this project are the XLUR12D [18], the WP154A4SUREQBFZGC [19], and the 5218559F [20]. The important factors to look at when selecting which LED to use is the voltage, color, light intensity, and cost. We want a cheap low powered option that is able to display green and red colors for the output. The LED must also provide enough light inside the device for the camera to view the bees. We have selected to go with the third option, the 5218559F LED manufactured by Dialight.

To begin, the 5218559F LED is reasonably priced at eighty-eight cents per unit, when compared to the other options. The 5218559F provides similar specifications to the WP154A4SUREQBFZGC, while being more than a dollar cheaper. The 5218559F has the highest millicandela rating, or light intensity, of any option. This is important to help light the inside of the device. Moving on to the color of each LED, the XLUR12D only displays the color red, while the other two options are RGB LEDs and can produce many different colors. Each LED has the same size diameter for the lens at five millimeters and height at eight point six millimeters. In terms of voltage, the 5218559F provides the highest peak voltage output at three point three volts with the WP154A4SUREQBFZGC as a close second at three point two volts.

Name	Cost per unit	Size of lens, diameter (mm)	Voltage (V)	Wavelength (nm)	Current (mA)	Millicandela Rating (mcd)
XLUR12D	$0.29	5	1.9	617	10	39
WP154A4SUREQBFZGC	$1.92	5	1.9 - 3.2	465 - 630	20	400 - 1700
5218559F	$0.88	5	2.2 - 3.3	470 - 625	20	1900 - 2500

Table 3.3.1.1: LED Comparison.

3.3.2. Display Screen Technology

For this project we will be utilizing a liquid crystal display (LCD) screen to show the response found from our device. When determining which display screen to select, we are mainly looking for a cost-effective screen with enough size to display data from the system. The screen should also have a low voltage consumption. Another consideration is that the LCD should not exceed the dimensions of the device. The LCD must be able to fit on the top of the device. This section will discuss the options that we considered in our research of this project. We also go on to selecting an LCD.

The first option is the NHD-C12832A1Z-NSW-BBW-3V3 [21], manufactured by Newhaven Display Intl with a cost of twelve dollars and eighty cents per unit. The size of the display is thirty-six millimeters by twelve millimeters. The resolution of the display is one hundred and twenty-eight pixels by thirty-two pixels, and it requires three volts of power. This LCD is the a cheaper and smaller option.

The next option is The C164A-YTY-XW65 [22], manufactured by Focus LCDs with a cost of fifteen dollars and eighty-four cents per unit. The LCD has a width of eighty-seven millimeters and a height of sixty millimeters. The display shows sixteen characters on four lines, and requires five volts of power. This LCD is limited on the amount of information that can be displayed, compared to the others. For that reason, this option is more if the desired data output is not significant.

The third option is The MIKROE-4 [23], manufactured by MikroElektronika with a cost of twenty-nine dollars per unit. The size of the display is sixty-two millimeters by forty-four millimeters. The resolution of the display is one hundred and twenty-eight pixels by sixty-four pixels, and it requires seventeen volts of power. This screen uses a KS0108 controller, this controller is not as common as the ST7920 controller.. This screen has the largest cost and power of our entire selection.

The final option is the LCD display module manufactured by Ximimark. The cost of this LCD screen is $9.99. This LCD uses a ST7920 controller to display pixels. This is a common controller within LCDs and has a lot of information online to compare with. The dimensions of this screen are ninety three by seventy millimeters. The resolution is one hundred and twenty-eight pixels by sixty-four pixels and the operating voltage comes in at about five volts.

We have decided to use the LCD screen by Ximimark. This screen is a great size to fit on the device while still maintaining a large screen to display the response. The resolution is the same as the MIKROE-4 but is twenty dollars cheaper. The price of this LCD comes in at $9.99, this is the cheapest option. Another factor is that this LCD uses a ST7920 controller. This is a more common controller than some of the other options we looked at, therefore in the case that we run into a bug then there is a greater chance of finding information on it to help solve our problem. To sum up, we believe that the LCD by Ximimark is the best option and will be using it in our device.

Name	Cost per unit	Size (millimeters)	Pixels	Power (Volts)
NHD-C12832A1Z-NSW-BBW-3V3	$12.80	36 x 12	128 x 32	3
C164A-YTY-XW65	$15.84	61.8 x 25.2	Shows 16 characters on 4 lines	5

Name	Cost per unit	Size (millimeters)	Pixels	Power (Volts)
MIKROE-4	$29.00	62 x 44	128 x 64	17
Ximimark LCD	$9.99	93 x 70	128 x 64	5

Table 3.3.2.1: LCD Display Comparison

3.4. Electric Components

3.4.1. Fans

Fans, simply put, are powered machines that create and control airflow. The BEESTING device, operating with trace particle detection, of course requires this airflow in order to both sample it for the bees and to clear out their testing chambers of any remnant particulates. However, given concerns for the bees and for our general operational efficiency, we have some serious considerations when it comes to actually selecting a viable fan. Namely, we need to consider the average level of sound the fan produces (normally recorded in dB), alongside both the fan size and the air flow (normally recorded in Cubic Feet per Meter - CFM). Low sound is a must for the bees, as is a small size to comfortably fit the fans into the device. Air flow is also important, albeit not as much as the prior two.

The first option is the YDM4010B12 by Anvision [24]. This is a small embedded fan with dimensions of forty millimeters by forty millimeters by ten millimeters - fairly small. This is about the size we're looking to work with. The airflow is 7.56 CFM with a decibel level of 27.5 dB. The fan speed clocks in at six thousand, two hundred rotations per minute (RPM) and a voltage of twelve volts. This fan is priced just under fourteen dollars for a pack of two.

The second option is the XS2 manufactured by NoiseBlocker, with a price of just a little under thirteen dollars per fan [25]. True to the manufacturer's name, the XS2 has a noise level of sixteen decibels, which is notably quite quiet. This low decibel level may be because of the fan speed that clocks in at only four thousand RPM, which limits the inherent vibrations across the fan itself. The dimensions of the fan come in at fifty millimeters by fifty millimeters by ten millimeters. This larger design helps increase the airflow to 6.8 CFM, even though the fan speed is not as fast as other options. Lastly, this fan operates at twelve volts.

The third option is the CG2510H12-IP67 - manufactured by Coolerguys - with a cost just under ten dollars [26]. The CG2510H12-IP67 is about the size of a quarter; coming in at twenty-five millimeters by twenty-five millimeters by ten millimeters, this extremely small fan manages to rotate significantly faster than the competition with an RMP of nine thousand. Even with this high fan speed, however, the airflow is lacking at 2.1 CFM. Additionally, the noise level of this fan hits up to twenty decibels, which is about our upper intended limit for noise level. This fan also uses twelve volts - like the previous fans.

The fourth option is MakerFocus' 3D printing cooler fan. This fan comes at a great price, just about six dollars a fan [27]. While being the same size as the YDM4010B12 fan, 40mm by 40 mm by 10mm, MakerFocus' fan is much quieter at 18 dB. The airflow for this fan is 5.75 CFM. Furthermore, this fan also uses 12 volts.

The table below shows all the important specifications for each fan. When looking at the size we can see that each fan is similar in size, other than the CG2510H12-IP67. The CG2510H12-IP67 is by far the smallest fan, which will be able to fit into some of the tight spaces of our design with ease. However, the airflow of the CG2510H12-IP67 is too small to consider this fan for efficient airflow. The first option, the YDM4010B12, has the highest airflow of any of the options we have considered, but the high noise level is of concern. The high noise level may interfere or scare the bees, thus this option is not the best to go forward with. The final two options have very similar specifications across the board. The XS2 is quieter and has greater airflow, but the fan by MakerFocus is smaller and cheaper. Ultimately, we have decided to select the NoiseBlocker XS2 because it is the quietest fan. The size increase in the XS2 also played a role in this selection, but we believe that it will be able to fit into our design. The XS2 is a great size and provides very little noise, while maintaining an adequate airflow. The quiet noise is essential in not disturbing the bees.

Name	Size (mm)	Noise Level (dB)	RPM	Airflow (CFM)	Voltage (v)	Cost
Anvision YDM4010B12	40 x 40 x 10	27.5	6200	7.56	12	$13.98 (for two)
NoiseBlocker XS2	50 x 50 x 10	16	4000	6.8	12	$12.95
Coolerguys CG2510H12–IP67	25 x 25 x 10	20	9000	2.1	12	$9.95
MakerFocus 3D printing cooler fan	40 x 40 x 10	18	5000	5.75	12	$5.99

Table 3.4.1.1: Fan Comparison Table

3.4.2. Power Supply

For keeping with the portability of our BEESTING device we need to consider different types of power supplies. Ideally we want something that can run the device continuously for roughly thirty minutes or more. Though our device will not be running in a continuous state, we want to ensure adequate battery life between uses and to have a reliable battery that can last longer between individual usage. We also will utilize a rechargeable battery so that during downtime the device can be recharged and continue to be reused. With it being rechargeable, we also want to allow for the battery to be swapped out with another battery if extensive use of the device is needed with no time in between to charge. Another important aspect is to ensure a proper power output and that the size of the battery isn't too large for our device or adds too much weight to the device. In terms of power output from the battery, regardless of strength, we want a battery that can output more than what our device requires, since our PCB design can limit output with resistors where it's needed.

We looked at three different rechargeable battery packs that can be utilized within our device. Each battery we looked at all fell within an equal number of Watt-Hour (Wh) of 90-100 Wh. The AI development board utilizes between seven to fifteen watts of power, the microcontroller, LEDs, and LCD will utilize significantly less than the AI development board. Since all of the batteries that were considered within the same range the difference between them came down to the other factors we considered.

The next important specification was the size of the battery. To keep with a portable device, we want to implement a battery that isn't too large or too heavy. We also have to make sure the battery can be implemented into our PCB design and be interchangeable with another battery. The dimensions for a Philips Respironics Battery Pack are considerably large in regards to length and width of the battery but has a very slim height. The battery also only weighs about 1.5 lbs which falls within reason for our purpose. Compared to the other batteries that have a larger height but slightly less width and length, this will allow for a better integration within our device. The weight of the other batteries like the AT:Tenergy are slightly, but not a large enough difference for it to be noticeable.

We also looked at the voltage and the Milliampere Hour (mAh). This was to ensure that the overall system and the boards being implemented have enough power to fall within our use time on our device. Even though each component has slightly different power requirements, it will still have an overall drain on the battery meaning that the voltage and mAh must be strong enough to power the equivalent of a laptop, which based on what we have looked at, far exceeds the requirement.

One last aspect we looked at was how the batteries are built. This was to see how it can be integrated into our PCB. For instance, the Philips battery is built for a respirator and will require use to adapt the battery for our personal use as we can't just tie leads from the battery to our PCB or integrate it into it. Both the AT:Tenergy batteries have bare leads and allow for PCB integration without having to adapt a major part of the battery. Though this would allow for ease of use, we believe the Philips battery is still a better use due to its very slim size.

Battery Packs	Watt-Hour (Wh)	Dimensions (mm)	Weight (lbs)	Voltage (V)	Milliampere Hour(mAh)	Temperature (℃)
Philips Respironics Battery Pack	~100 Wh	107.95 x 190.5 x 31.75 mm	1.5 lbs	14.4 V	6600 mAh	Data can not be found.
AT:Tenergy Li-ion 18650 *(btw this battery explicitly states PCB usage)*	97.68 Wh	73 x 68 x 55 mm	1.27 lbs	14.4 V	6600 mAh	Discharging temperature 10~60 ℃, Storage temperature 0~30 ℃.
AT:Tenergy Li-ion 14.4 V (Different arrangement of battery pack)	100.8 Wh	147 x 73 x 20 mm	0.93 lbs	14.4 V	7000 mAh	Discharging temperature -20~60 ℃, Storage temperature -20~20 ℃.

Table 3.4.2.1: Battery Pack and Power Supply Comparison.

3.4.3. Switch

To begin, a switch is an electrical component used to help toggle a connection. The job of a switch is pretty simple. The switch is either closed or open to control the signal flow of the circuit. For this project, the switch will be used to turn on power through the system. By toggling the switch the user is able to turn on or off the system. This will put the system into an idle state. The main factors to look for in the switch are the dimensions, current, and the cost.

The first option is the KCD1-01 [28]. This switch is manufactured by QTEATAK and the price is $6.99 for a pack of five switches. These switches are very common, they look like the type of switch one would find on a vacuum. This generic switch can come pre-wired or with pins. The current of this switch is about six amps at two hundred sixty volts or ten amps at a hundred twenty five volts. The dimensions of the switch are twenty one by fifteen by twenty five millimeters.

The second option is the micro slide switch manufactured by Uxcell [29]. The price of this switch is $7.99 for five switches. This is a slide switch. For the first option, the user will press down on either side of the switch to toggle, while for this second option the user will slide the switch to toggle. The max current for this switch is just half an amp. The dimensions of this switch are fifteen by seven by seven millimeters.

The third option is the MTS102 [30]. This switch is manufactured by Gikfun and the price is $8.98 for a pack of ten. This is a two position toggle switch with pins. This option is made out of metal and resembles the kind of switch you would find many electrical projects. Being made out of metal, this is the most durable option. The max current comes in at 6 amps. The dimensions of the switch are thirty by fifteen by thirty three millimeters. This makes the MTS102 the largest of the three options.

The table below compares the varying options for switches. The first option has the lowest cost and same max current as the third option. While the second option has the smallest max current of half an amp, as well as being the smallest in size. We have decided to go with the first option, the KCD1-01. This option satisfies the factors that we are looking for. The dimensions of this switch fit well into our device, while the other two options were either too large or small. In addition, the first option was also the cheapest of the three.

Name	Size (L x W X H)	Current (Amps)	Cost
KCD1-01	21 x 15 x 25 mm	6	$6.99
Micro slide switch	15 x 7 x 7 mm	0.5	$7.99
MTS102	30 x 15 x 33 mm	6	$8.98

Table 3.4.3.1: Switch Comparison Table.

3.4.4. Button

The next part that we will discuss is a button. The button will be placed on the device to start many of the processes. When considering a button, there are not many concerning factors that we need to consider because the button has a simple job of starting the processes of the system. The main factors to consider will be the size and functionality. We just need a simple button, there is no need to make the button complex.

The first option is the push buttons from Weideer [31]. These buttons come pre-wired and ready to be mounted on. This button is priced at $8.99 and comes in a pack of five. Each button is a different color. The colors are red, black, green, yellow, and blue. Having the button be a different color will help to contrast the button and make it stand out rather than blend in with the rest of the device. This button comes with a pre-threaded mount. The diameter of the thread mount is 15.5 millimeters. The dimensions of the button are twenty four by sixteen by sixteen millimeters. The rated voltage and current is one hundred twenty five volts and six amps.

The second option is the Coolais momentary push button [32]. This button comes pre-wired and ready to mount as well. Although this pack of five buttons do not come in different colors. The only color is black, but the button does have an option to come flat, flushed with the sides, or high. The price for this button is $12.99. This increase in price may be because the button is made out of aluminum. The diameter of the thread mount for this button is twelve millimeters. The dimensions for this button are a length of fourteen millimeters and a width of fourteen millimeters. The rated voltage and current is two hundred fifty volts and five amps.

The third option is the momentary push button manufactured by Lkelyonewy [33]. The price for this button is $11.49 for twenty four pieces. Unlike the previous options, this button does not come pre-wired and soldered. This button has two pins for wired attachment. The button comes in six colors: red, white, black, blue, yellow, and green. The diameter of the thread mount is 16 millimeters. The dimensions of the button are twenty four by twenty by twenty millimeters. The rated voltage and current is two hundred fifty volts and three amps.

In comparison, the first option is the cheapest and has the lowest voltage. The second option is the most expensive. The third option may be more expensive than the first but come with more buttons. Although these extra buttons are not needed. The option is also the largest of the three, coming in with a diameter of twenty millimeters. After considering each option, we have decided to pick the first option. This is because we believe that the second option is too small and only comes in one color. The single color may blend in with the rest of the device and decrease the user's accessibility. While the third option is a good price for how many pieces one gets, it is more buttons than needed. The first option is a good size, comes in many different colors, and the cost is low. The table below helps demonstrate the comparisons between each button.

Model Number and Manufacturer	Dimensions (millimeters)	Installation diameter (millimeters)	Current (amps)	Voltage (volts)	Cost
CA-R13-507-5-X, Weideer	16 x 16 x 20	15.5	6	125	$8.99
PBSM-12, Coolais	14 x 14 x 20	12	5	250	$12.99
Lkelyonewypbs01, Lkelonewy	20 x 20 x 24	16	3	250	$11.49

Table 3.4.4.1: Fan Comparison Table.

3.5. 3D Printing Components

The design and building of this project will require a considerable number of specialty parts. From the outer hull of the device itself, to the small harnesses made to hold the bees in place, they will all be designed, extruded via 3D printer, and tested in-house by our group. That means that a significant amount of time and care must be invested into how we plan to 3D print these parts.

3.5.1. 3D Printing Filament

Ideally, the best type of filament for this project would be some type of nylon filament - some of the strongest and most durable filament out there - but sadly, there is a critical complication with this. When unused nylon filament is left out in the open air, it will absorb the moisture in the air and lose structural integrity. Typically, this is not a significant problem so long as local humidity is low on average. As we live in Florida, a coast-surrounded peninsula, humidity is constant and high across a vast majority of the state. Even if stored correctly, the nylon would still always risk the possibility of being compromised by nothing other than nature itself. As such, we have instead chosen to look into acceptable alternatives, of which we reduced the selection down to only four.

Filaments	True Diameter	Dimensional Accuracy	Density	Volume	Price
MatterHackers Black MH Build Series ABS	1.75mm	± 0.03mm	1.25g/cm	0.80L	$20.87
MatterHackers Black PRO Series ABS Filament	1.75mm	± 0.02mm	1.04g/cm	0.96L	$52.00
Overture ABS Filament	1.75mm	± 0.02mm	1.18g/cm	0.97L	$21.00
MAKERBOT ABS	1.75mm	± 0.02mm	1.12g/cm	0.86L	$69.00

Table 3.5.1.1: 3D Printer Filament Options.

We choose to compare these four filaments because these are the filaments which our group, namely Nicholas, has had the most experience with from modeling, designing and printing when it comes to his research group. The top three choices would have to be the MatterHackers Black PRO Series ABS Filament, the Overture ABS Filament, and the MAKERBOT ABS. Additionally, the MatterHackers Black PRO Series ABS Filament is likely to not make the cut, as during practical use, it has an unfortunate tendency of bonding to the dissolvable support material while printing. This in turn leaves holes and gaps in the final print, threatening structural integrity. When it comes to a closed air system, such complications are simply unacceptable, hence the high likelihood it will not be used in the final project.

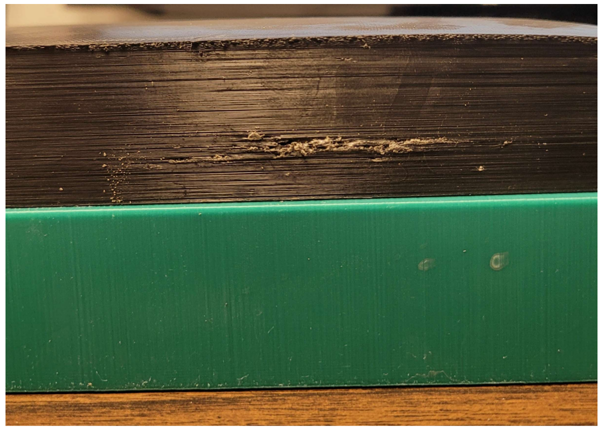

Figure 3.5.1.2: MatterHackers Black PRO Series ABS compared to Overture ABS Filament green.

The last two filaments are the Overture ABS Filament, and the MAKERBOT ABS. Each of these filaments have their distinct advantages and disadvantages when it comes to the 3D printing process, resulting in both of them being viable when it comes to producing the final product.

The MAKERBOT ABS filament, by Nicholas's experience, typically has the hardest time sticking to the printing sheet. This leads to several reprints and a possibility of internal messes within the 3D printer itself. However, its accuracy for slits, slots, and high-fidelity holders and mounts for critical pieces - such as our optical lenses. The Overture ABS filament is notably cheaper - under a third of the price of MAKERBOT - and still is notably accurate without the similar issues. As such, making use of the Overture ABS filament for a majority of the project's framework and MAKERBOT ABS filament for the specialist pieces is the most likely compromise.

3.5.2. Filament Thickness and Printing Nozzle

To pair with the filament, we must also choose the thickness of the filament and the size of the nozzle. For general purpose, the two main sizes that filaments tend to come in are either 1.75 millimeters, or 2.85 millimeters. Considering the fact that we are working with bees - which are notably small in size - and working with multiple parts that need stringent size requirements, it would be best to use the smaller-thickness filament. Ergo, the 1.75 millimeter thickness for the filament is the probable best choice for the project. Applying similar logic to the selection of printing nozzles, a 0.4 millimeter nozzle should yield consistent results at a minor sacrifice of longer print times.

3.5.3. Methods of Joining 3D Printed Parts

3.5.3.1. Glue

Adhesives are a method of permanently affixing components. Superglue or epoxy is applied to the faces the user wants to join while in a liquid state. The adhesives will spread across the joined faces, seeping into small crevices and covering as much surface area as possible. As time passes, the liquid dries into a dense solid that bonds the components together. If desired, the space around the seam can then be sanded to reduce its visibility.

Alternatively, acetone can be used as an adhesive. The chemical dissolves 3D printer filament. If applied to the faces the user wants to join, the surfaces will begin to break down. They can then be affixed and left to dry. As the acetone evaporates, the parts resolidify into a single solid piece. This method is more permanent than using glue, so should only be utilized if the parts should never be separated.

Heat-set inserts are hollow brass cylinders that are threaded internally. They are designed to be installed in another component to house a screw, which can then be used to join parts together. To perform the installation, the insert can be heated with a soldering iron and pressed into a hole in a 3D printed part. A screw is then twisted through and driven into another heat-set insert on a different part. Several factors affect the performance of these inserts, including how smooth the part's exterior is and how far it has to extrude. Regardless, these metal parts are stronger than 3D printed threads. They can withstand more torque than the soft plastic and boast more mechanical strength. This in turn leads to lower rates of mechanical failure.

Heat-set inserts are easy to add to a design, only requiring a hole to be added. They also add a professional element to a design's appearance. The downside of these parts is that they cannot be recovered; any error in placement means a new component must be printed. This can also lead to complications if a design needs to be repaired, but this concern can be mitigated by using heat-set inserts alongside other joinery methods.

Nuts and bolts are a traditional method of joining parts. A threaded dowel (the bolt) is inserted through a hole and fastened on the other end with a nut. There are many benefits to using this method. The metal components can handle more torque than plastic printed threads. Additionally, metal can be used in conjunction with magnets to create easily separated parts. Most design software also comes with built-in options to facilitate nut and bolt use. These programs will allow users to place a hole anywhere in the design. Hexagonal indents can be added so the bolt is flush with a surface if desired.

3.5.3.2. 3D Printed Threads

3D printed threads are a spiral embossment that is incorporated directly into a design. It can be combined with screws to join parts together. Most modeling software has a threading feature built in. All a user has to do is select the space where a threaded hole should be. The program will add in the threading itself and take tolerance into account. These threaded holes can then be used with metal bolts and screws, or 3D printed threaded rods.

The threading features in modeling software make this joinery method easy to design. However, it comes at a drawback. Since plastic is a fairly weak material, there is a potential for the threads to rip and for mechanical failure to occur. If this happens, the component would have to be reprinted since threading is not repairable

3.5.3.3. Snap Fit Joints

Snap fit joints are some of the most effective but simplest ways to assemble your parts. By using snap joints, you eliminate the need for excess tools for assembly by nuts, bolts, screwdrivers, and glue. There is a reason why almost all kids' toys use snap joints. The basic idea of a snap fit joint is that you have a part the a small obtrusion that sticks out with a hook or stud. You then have another part with slotted holes that are just big enough for the stubs of the obtrusion to squeeze through by flexing on its way in and then relaxing once it is inserted. This will keep the male part from easily sliding off. as you'll have to apply pressure to the part inorder to cause flexion of the obtrusion, otherwise it will be difficult to get it out. Depending on the shape of the snap joint, the connection may be temporary or permanent.

Plastic is by far the preferred material for snap fit joints, as it has amazing levels of strain and elasticity, meaning that you can manipulate the snap joint to a large extent before it fails. Typically and ideally, you would want your snap joints to be free of load when joined. This is quite important when using plastic as your material, as plastics that are constantly under a load will undergo gradual deformation under the stress of the load, this will cause the joints to slowly lose their connective strength over time and become useless. For our BEESTING system we will be using several snap fit joints for the handheld devices for place that the operator needs to have easy access to on the go such as the battery compartment to exchange the battery once it has been drained and a separate compartment used to insert and take out the devices usb storage to retrieve your recorded data. For the battery pack i've decided to use a type of torsion snap joint.

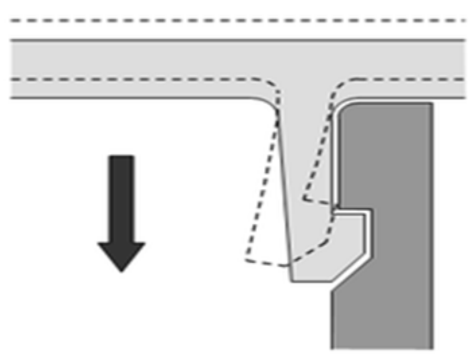

Figure 3.5.3.3.1: Diagram of a Snap Fit Joint.

As it is a relatively simple but extremely effective snap joint. A torsion snap fit works by deflecting the stress of the beam by twisting the bar; the deflecting force of the rocker arm is the force that creates the torsion of the shaft. When designing the torsion snap joint there are a lot of factor we must keep in mind as if the rocker arm is to long or short that that connection won't last to long and if it is to thin the male snap piece will be likely to snap and break to figure this out we will be making use of some snap fit design calculations and formulas.

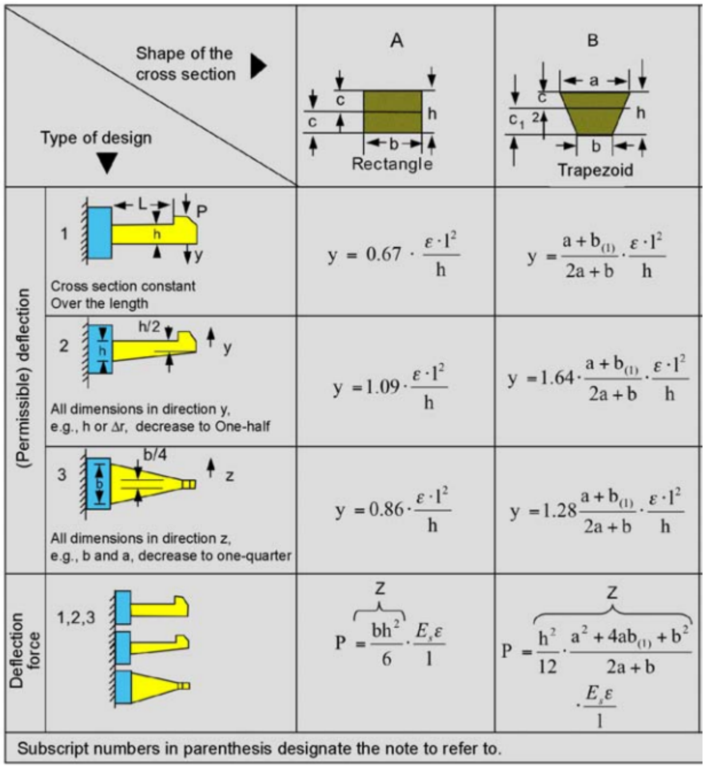

Figure 3.5.3.3.2: Diagram of equations for Snap Fit Joints.

Variable	Definition of Variable
y	(permissible) deflection (=undercut)
E	(permissible) strain in the outer fiber at the root; in formulae: E as absolute value = percentage/100
l	length of arm
h	thickness at root
b	Width at root
c	distance between outer fiber and neutral fiber (center of gravity)
Z	section modulus Z = I c, where I = axial moment of inertia

Variable	Definition of Variable
Es	secant modulus
P	deflection force
K	geometric factor

Table 3.5.3.3.1: Variable List for Figure 3.5.3.3.2.

As stated before, by the nature of snap fit joints, in order for them to work flawlessly as intended we must figure out and calculate the perfect size of each piece. But we must remember that we are still using a 3D printer to make these parts, and 3D printers have their own slew of problems as the parts tend to expand past their original modeled size. To better combat this, we will proceed to print a number of rocker arms at different thicknesses and observe the rate of over expansion with a caliber that will allow us to later perfectly print the torsion snap joints for the final product.

3.5.3.4. Nuts and Bolts

Nuts and bolts are a traditional method of joining parts. A threaded dowel (the bolt) is inserted through a hole and fastened on the other end with a nut. There are many benefits to using this method. The metal components can handle more torque than plastic printed threads. Additionally, metal can be used in conjunction with magnets to create easily separated parts. Most design software also comes with built-in options to facilitate nut and bolt use. These programs will allow users to place a hole anywhere in the design. Hexagonal indents can be added so the bolt is flush with a surface if desired.

3.5.4. CNC Milling for Fabrication of The Lens Housing Unit

When dealing with visual optics and lenses, you tend to be working with extremely narrow tolerances in order for the given optical system to properly function. For example, in a laser cavity if the reflectivity of the mirrors in the cavity are reduced by three to six percent, you'll see drastic performance penalties. Similarly, in an imaging system such as ours, if things are just slightly off the image will come out blurry and become useless for its intended purpose. Even with some of the most cutting-edge 3D Printers on the market, the tolerances in which we are dealing with will likely lead to a multitude of faulty prints, and an undeniable waste of both time and resources. That is why we will be additionally making use of Computer Numerical Control (CNC) Milling.

Milling is the process of machining - better known as cutting into shape - an object or compound using rotational cutting implements. There are a wide variety of applications for such a process, but in this particular instance it can be used to carve the housing for our especially critical Lens Housing Unit. However, ordinary milling is often human-operated; this is a problem when a precision down to a fraction of a millimeter is a necessity. As such, the solution is CNC Milling.

Versus other forms of milling, CNC Milling makes use of extremely high fidelity inputs from an operator that uses a form of machine-specific pseudocode, allowing for exceedingly complex and specialized designs. CNC Mills are capable of multiaxial movement - not just operations in the traditional X, Y, and Z planes, but also the ability to rotate in the X and Y dimensions. In some cases, CNC Mills can operate with even 12-axis movement; the technology is simply phenomenal. With this, we can most certainly get the precision that we're looking for.

There's a problem, of course. Namely that mills tend to be on the expensive side, and CNC Mills drastically moreso. Additionally, CNC Mills take up a significant amount of space, electricity, and specialized tools - or in the case of some versions of the machine, specialized access to water for pressure-cutting. Additionally, given we're only using the CNC Mill for one project, it would be incredibly irresponsible to consider purchasing one. Thankfully, there's already an existing demand for using CNC Mills in the name of highly specific pieces and parts, and as such it's fairly easy to find machining shops that can take a custom order that can handle the necessary prerequisites we desire.

Of course, actually researching a good machining shop is more a challenge of finding one with a CNC Mill possessing the desired traits. Specifically, we're looking for Chassis Rigidity, Rotations Per Minute (RPM), Motor Resolution, and Machining Accuracy. Chassis Rigidity is effectively how much the resulting final product tends to warp or shift after being milled into shape; this can be and is affected by the machining processes undertaken. RPM is referring to the rotational speed of the drills - a faster drill tends to result in faster milling, which means a faster final product. Motor Resolution is the 'smoothness' of the mill - effectively the precision of the drills to achieve consistent, practically-flawless shapes. Machining Accuracy is similarly important, simply assuring that the resulting mill follows the intended design as closely as possible.

Knowing what we're looking for, we can now get into the actual capabilities of the machines in question. The first machine that we will be looking at will be the Avid PRO4896 4' X 8' CNC ROUTER MACHINE. The Avid PRO4896 boasts an impressive 49" by 98" cutting area with the ability to cut materials like softwood, hardwood, plywood, high-density plastic, foam, balsa, MDF, baltic birch, and aluminum. The linear motion of the Avid PRO4896 is controlled by two NEMA-23 stepper motors, as opposed to simpler DC motors. This gives the Avid PRO4896 additional control and precession. A typical DC motor uses rotors, armature, and carbon brush, and works in a continuous flow in which the brushes are always in contact with the armature. On the contrary, Stepper motors are brushless and are made of rotors that consist of multiple evenly-spaced windings and a stator that has perpetual magnets. The stepper motor controller uses its sets of coils to rotate the rotor. The amount of steps a stepper motor has tells us how many degrees of movement the motor moves with each step, giving us the most superior range and control of movement compared to any other commercial motor. One of the biggest driving points towards choosing the Avid PRO4896 is that it is equipped with a spindle as opposed to the typical router. The biggest difference between a spindle and a router is the power and torque, this is very important especially for our project as increased torque will proportionally increase the depth at which we can cut into the material. Also using a spindle lets us manipulate the RPM (revolutions per minute) of the CNC machine, typical CNC machines use a makita router which is a form of compact routers that perform extremely well but are harshly limited in terms of their range and variability of the output of the RPM at a range of just ten levels, ranging from medium to extremely high speeds of RPMs. on the other hand spindles are equipped to be able to work at very low RPMs which means that the CNC milling machine will be able to work on a larger range of materials such as non-Ferrous metals like aluminum, copper and brass which are the exact materials we would like to use. The last point on the Avid PRO4896 is its optional upgrade piece that lets it work with a fourth axis.

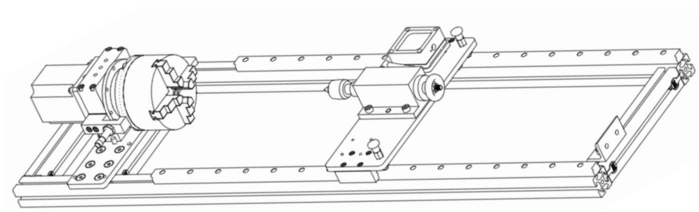

Figure 3.5.4.1: A Rotary CNC Mill.

The rotary axis uses a NEMA-34 stepper motor and is equipped with a five-inch jaw chunk so that we can work with moderately large parts. The NEMA-34 stepper motor is able to spin the jaw and the strapped in material at a max speed of a hundred rotations per minute. The real jewel that sets this fourth axis (rotary axis) addon apart from other brands is that Avid provides software-guided alignment for the rotor, letting it become fully integrated with the Auto Z and corner-finding touch plate programs, enabling all three to work seamlessly with the Mach4 software. This enables the controlling drivers to post process the inverse time feed rates from the spindle rotating the drill bit, the two NEMA-23 stepper motors controlling the X and Y axis and the NEMA-34 stepper motor controlling the rotary axis eliminating the possibility of position lag of the CNC machine that could lead to large reductions in quality and more imperfections in the resulting piece.

The next CNC milling machine is the ShopSabre 23. The ShopSabre brand is a strong and reliable brand that has been operating for over twenty years, and it shows with were equipment. The ShopSabre 23 has a smaller cutting area at 30” by 40” and is capable of milling materials such as acrylic, foam, plastic, wood, and aluminum. The ShopSabre 23 is easily able to one up the Avid PRO4896 CNC machine with its stronger and much more rigid steel chassis compared to the lower performing aluminum chassis of the Avid PRO4896. The rigidity of your CNC milling machine is extremely important for example let's say the that your Z axis which holds your spindle is a bit looser and more susceptible to movement and vibration at the point where this part attaches to the gantry / bridge of the cnc machine this will cause all movements of the spindle to be slightly exaggerated overtime reducing the overall quality of the part. The ShopSabre 23 is also equipped with wiper blocks on the linear motion rails these keeps the rails clean and ensure that the machine operates as smooth as possible and because these machines are operating in commercial environments were there running constantly 24 / 7 this buildup can really be significant and hamper performance especially if the employees fail to properly clean the machine before after and during each cut making this feature extremely enticing in a commercial setting. The spindle equipped in the ShopSabre 23 hase a range of 10,000 - 21,000 RPM which is a bit on the high side when dealing with non ferrous metals like aluminum. The rest of the ShopSabre 23 is pretty standard with nothing else really standing out as overwhelmingly positive or negative compared to the other systems.

Figure 3.5.4.2: The inside of the Makera Cavera.

The last option for our CNC milling machine is a very new machine from an also very new company call Makera, in september 2021 Makera launched a kickstarter campaign for their new and revolutionary compact smart CNC milling machine called Carvera: The Fully Automatic Desktop CNC and amassed nearly 2 million dollars in funding in a few weeks. The carvera truly is a revolutionary CNC machine even though the Carvera is a small compact CNC milling machine it boosts a steel chassis to give it a strong rigidity that can compete with the ShopSabre 23. Due to its compact size the working area of this CNC milling machine is only 14.2” by 9.4” which is still enough for us to use it for our purposes. The Carvera milling tool is powered by a very impressive spindle that can achieve RPMs from 0 - 15000 with a built in air cooling system. The linear motion system of the CNC machine uses NEMA 17 stepper motors with a drive system using ball screws on linear rails for vibration-free stability and precise motion, this enables a transversal speed of 236 inches per minute. The Carvera is able to get an impressive motor resolution of 0.002 inches and a spindle runout of 0.0003 inches this on average depending on the drill bit that you are using should be able to a machining accuracy of up to 0.002 inches.

But the Carvera doesn't just stop there, as it boosts several other game changing features. The Carvera markets itself as fully automatic, and it truly is, as it comes with the ability to fully change and swap out its drill bit in the middle of the session as it has a total of 6 different drill bits plus a special bit that's used to auto probe the work area which is normally a very time intensive and tedious job that if not done right will lead to disaster later on are the cnc machine was not accurately leveled or synced up to the material. The CNC machine also comes with a built-in dust collector to keep debris out of the linear rail system, and ensure that the machine is running at peak performance at all times. Mounted right next to the drill bit is an integrated 2.5 W laser module. The Carvera CNC milling machine is capable of machining non Ferrous metals such as aluminum, brass and copper. Surprisingly we learned that the Carvera is also equipped to perform our own PCB fabrication with their own proprietary software that enables easy use and generation for the action for fabricating your own PCBs.

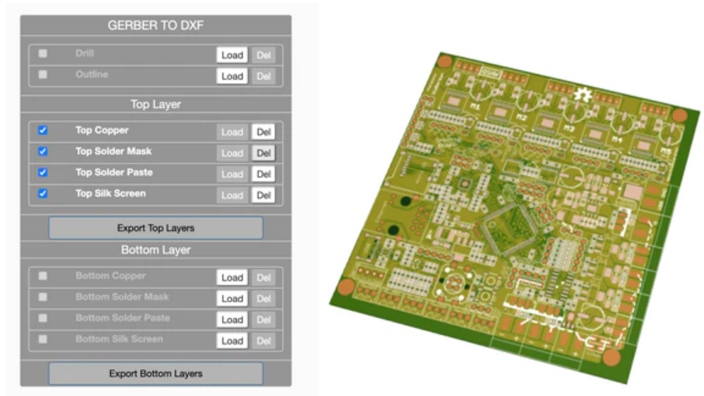

Figure 3.5.4.3: An example of the Makera Cavera building a PCB.

	Chassis Rigidity	Spindle RPM	Spindle Runout	Motor Resolution	Machining Accuracy
Avid PRO4896 4' x 8' CNC Router	Fair	1000 RPM - 18000 RPM	0.0002 in	0.0005 in	0.005 in
ShopSabre 23	Excellent	10000 RPM - 21000 RPM	Not provided	Not provided	Not provided
Carvera: A Fully Automatic Desktop CNC	Excellent	0 RPM - 15000 RPM	0.0003 in	0.0002 in	.002 in

Table 3.5.4.1: Comparison of CNC Mills.

In the end, we decided to use the Cervera for the fabrication of the lens system based on the high quality of the CNC machine plus the user friendly software and the ability to transfer all of those learned skills into fabricating our PCB on the Carvera. Also using the Carvera should be able to save us a substantial amount of money between machining cost for the lens system and the cost of fabricating our PCB.

3.6. Embedded System Components

3.6.1. AI Development Kits

An AI development kit, which consists of an SBC (Single-Board computer), will need to be implemented into the device that we plan to create. AI development kits allow for the creation and running of AI or machine learning algorithms separate from a laptop or desktop which means portability. Using a development kit, we plan to upload our machine learning algorithm and software to the development kit so that we can analyze the bees' proboscises within the device and make accurate conclusions within the device. When considering what AI development kits to use we had to look at several different options. Since the goal of this project is to be somewhat cost effective, we need to have a reliable development kit that can handle the workload given to it. This device must also be considerably small since it needs to fit into a portable handheld device. When looking at performance a few things need to be considered with importance as well. It's important that the development kit has strong CPU and GPU capabilities as the algorithm will be looking at five different bees at once and will need to identify the object specified. Considering what we looked at we narrowed it down to three different AI developer kits which are the NVIDIA Jetson Developer Kit, Raspberry Pi, and Google's own line of AI development kits.

3.6.1.1. Comparison of AI Boards

Between the three choices, each development kit had its pros and cons. Based on this we looked at each of them considering the most important factors of the kits and what each kit performed better at. The two development kits that seemed to have an overall better performance would be both the NVIDIA Nano kit and the Google Coral Development board [34]. When it comes to cost though the raspberry pi is significantly cheaper than its counterparts but does perform at a lower level than them which is expected. Another point that we looked at is what these boards are considered to be between FPGA or MCU. Each board that was looked at is considered a MCU since they are equivalent to small computers that can run an OS or similar and run applications through them, especially the Raspberry Pi 4 [35]. We also have no need to rewrite any hardware within the AI development board as each one can utilize what we need with what is available on the board.

One of the first components we looked at was the GPU/AI accelerator. Though a GPU is not necessarily required, it does provide benefits for computing data efficiently which allows for better real-time application, which is something we want our system to run in. For instance the 128-core Maxwell on the NVIDIA Jetson Nano is extremely powerful when compared to its counterparts and allows for heavy workloads in regards to machine learning [36]. Being that our project is utilizing object detection and requires machine learning, this is considerably one of the most important factors. The Raspberry Pi 4 lacks in raw power compared to the NVIDIA board, though it is not weak. It does not have nearly the strength that the NVIDIA kit has which could make computational times slightly slower. The Google Coral Development Board is considered to be one of the most powerful and can run TensorFlow, something we will be using to train our model, but with that being said does have one immense drawback is that it can not display video which is something that would be utilized during testing.

The second biggest factor when choosing the type of board was to look at the CPU of each. Having strong processing power is important to image processing. Since our project will be pulling a lot of data from the camera to analyze, being able to process the images for image analysis is a key aspect of the project. The NVIDIA Jetson Nano has a weaker CPU, but the speed difference between that and the others isn't significant enough to generate much of a difference [37]. The Raspberry Pi 4 has multiple options for CPU power and has an option up to 1.8 gigahertz (GHz), thus boasting a strong performance overall yet is overall weaker still then the Google Coral Board which has the strongest CPU over them, all utilizing both its processor and coprocessor, the Edge TPU which itself can perform four terra operations per second (TOPS). In consideration for what we need, power here is important, but at the same time more of the power for computation will come from the GPU with support from the CPU. With that in mind, the CPU will not need to have immense power and can allow us to relax without having to go with the best.

Memory for our board is another consideration that we looked at with regards to our needs. Our board needs to have decent RAM to allow for real-time computations. This requires memory that can perform at a high bandwidth and low latency to maximize those computations [38]. The NVIDIA Jetson Nano Boards has four gigabytes (GB) of memory at 1600 MHz which is equal to what the Google Coral development board has but does have the option for less memory at one GB. One issue though for the Google Coral is that currently there is no availability for the four GB board which for our purposes anything less then that will not meet our demand. It is better to ensure that we have more power than we need to allow for the fastest computations within our system leading to the real-time response we want. The Raspberry Pi 4 for instance, has many options for its memory going all the way up to eight GB, the most between the three boards. With that in mind this provides more than enough memory then what we would need, the only issue was finding the speed of the memory. Regardless of that, four to eight GB would serve for our purpose. Due to the similarities between both boards, the memory is something that will not create a large factor in our decision besides the eight GB option from the Raspberry Pi.

Another important aspect that we took into consideration for the board was the Storage. The reason being is that this board is being implemented within its own system and that it will require some level of storage, especially to hold the dataset that we plan to train the model with. When looking at each board though it became clear that between the three they all had the option for a MicroSD slot allowing us to decide what we would use for the memory. The Google Coral Development Board is the only one with built in storage which is eight GB of eMMC memory which is basic and not a lot of storage. That being said all boards support the option for microSD and once again for our purpose, having more will allow for us to store a larger dataset and train our model properly on the board.

Next we looked at size, since this needs to be implemented into a device that is hand held. Luckily all of the development boards are not so large that they would be considerably too big to implement and integrate into our device. The NVIDIA Jetson Nano was the largest of three, especially when compared to the Raspberry Pi 4. Since the sizes don't vary massively though this gives us freedom to pick more according to the other specifications we need, allowing us to opt for power without having to heavily consider whether it will fit into our design or not.

With the new design changes, only one camera is going to be utilized within the project meaning that this opens the options up for the boards. Previously the NVIDIA Jetson Nano was the only one with the ability to support two cameras. But with only one camera implementation, this allows for the options for all three boards. The camera that we plan to use has a USB 2.0 connection port which is technically only available on the Raspberry Pi 4, but to our benefit the USB 3.0 ports that are available on the other boards have backwards compatibility.

The last important aspects we took into account were both power supply and the cost of each board. When looking at each one, they all fall within a fair price point. Since we want to minimize costs for our project and make it as cost effective as possible while maintaining the most power we can get, each board has its drawbacks and benefits in regards to cost. Though the Raspberry Pi 4 for instance is the cheapest, even with the increased performance at the higher end of its options, it still underperforms in certain aspects that we are considering. The Google Coral is the most expensive but due to the unavailability of the four GB board and not knowing when it will be available makes it a less than likely option. The NVIDIA Jetson Nano falls between both of the aforementioned boards and can perform well above the level that we will need it for. In regards to power, we want to minimize the overall power consumption of the board to ensure the system can operate without massive power supplies. The Google Coral requires the most power compared to the other two boards which require slightly less. The NVIDIA Jetson Nano is more power efficient at its performance level and is about equivalent with the Raspberry Pi 4, which has slightly less performance then the NVIDIA Jetson Nano.

	NVIDIA Jetson Nano Development Kit-B01	Google Coral Development Board	Raspberry Pi 4 Model B
GPU/ AI accelerator	128-core Maxwell @921 MHz or 472 GFLOPS	Integrated GC7000 Lite Graphics/ Edge TPU 32 GFLOPS 32-bit or 64 GFLOPS 16-bit with 1.6 Gigapixel/sec	Broadcom VideoCore VI at 500 MHz Operates at 13.5 GFLOPS
CPU	Quad-core ARM A57 @1.43 GHz	NXP i.MX 8M SoX (Quad Cortex-A53, Cortex-M4F)	Quad-Core Cortex-A72 which is available at 1.5 GHz or at 1.8 GHz.
Memory	4 GB 64-bit LPDDR4 25.6 GB/s 1600 MHz	1 or 4 GB LPDDR4 1600 MHz maximum	4 possible memory options at 1, 2, 4, or 8 GB
Storage	microSD which is not included. This would be something we would obtain separately and for our needs.	Has 8 GB eMMC and a MicroSD slot. MicroSD does not come with the kit.	Has a microSD slot for storage and has USB Boot Mode.

	NVIDIA Jetson Nano Development Kit-B01	Google Coral Development Board	Raspberry Pi 4 Model B
Size	100 mm x 80 mm x 29 mm	88 mm x 60 mm x 22 mm	85.60 mm x 56.5 mm x 17 mm
USB Ports For camera.	Has 4x USB 3.0 Ports and one USB 2.0 Micro-B Port.	Lacks direct USB Ports but has a 24-pin FFC connector for MIPI-CSI2 camera (4-lane).	2x USB 3.0 Ports and 2x USB 2.0 Ports.
Encoder	Encodes at 4K at 30 fps, 4x 1080p at 30 fps and 9x 720 at 30 fps.	Nothing on encoding could be found.	1080p at 30 FPS video using H.264.
Decoder / VPU (Video Processing Unit)	Decodes at 4K @ 60 FPS, 2x 4K @ 30 FPS, 8x 1080p @ 30 FPS	Has extensive video decoding for 4K at 60 fps with HEVC/H.265 main as well as 1080p at 60 fps MPEG-2, MPEG-4p2, VC-1 and other options.	4K at 60 FPS video using H.265, 1080p at 60 FPS video using H.264.
Power Supply	Kit has two options. Micro-USB 5V 2A, DC power adapter 5V 4A	Requires a 5V 3A USB-Type C cable for power.	Utilizes a USB-Type C cable for power at 5V. Can Also use GPIO.
Cost	$100-$148	$175.99 for 1 GB Est. $200 for 4 GB but is out of stock.	$35, $55, $75 depending on which option is chosen.

Table 3.6.1.1: Comparison Table for the AI Development Kits.

Even with a specifications breakdown the boards still have certain design functions or features that are implemented within the kit that allow for easier development and AI usage. The NVIDIA Nano kit is designed to cover all aspects of AI frameworks and to handle modern AI workloads from image classification to speech processing. It also covers object detection, which is what we will be utilizing it for. The kit also has extensive I/O functionality to allow for a wide range of connectivity between different types of sensors. It also comes with NVIDIA JetPack which is a support package for the development kit that includes libraries for deep learning, computer vision and other uses. The Google Coral development kit was designed with machine learning as a focal point within a small form factor. Due to its machine learning focus it would be an ideal development board to utilize as well within our device. The only issue is the price can be a bit steep and the availability is uncertain when considering the four GB version of the board. The Raspberry Pi 4 Model B, in comparison to the other two boards is very cost effective but brings the question if it is effective enough for the workload, we plan to put it under. It also seems that it only allows for the utilization of cameras that are specific for the board or certain web cameras which might limit our capabilities.

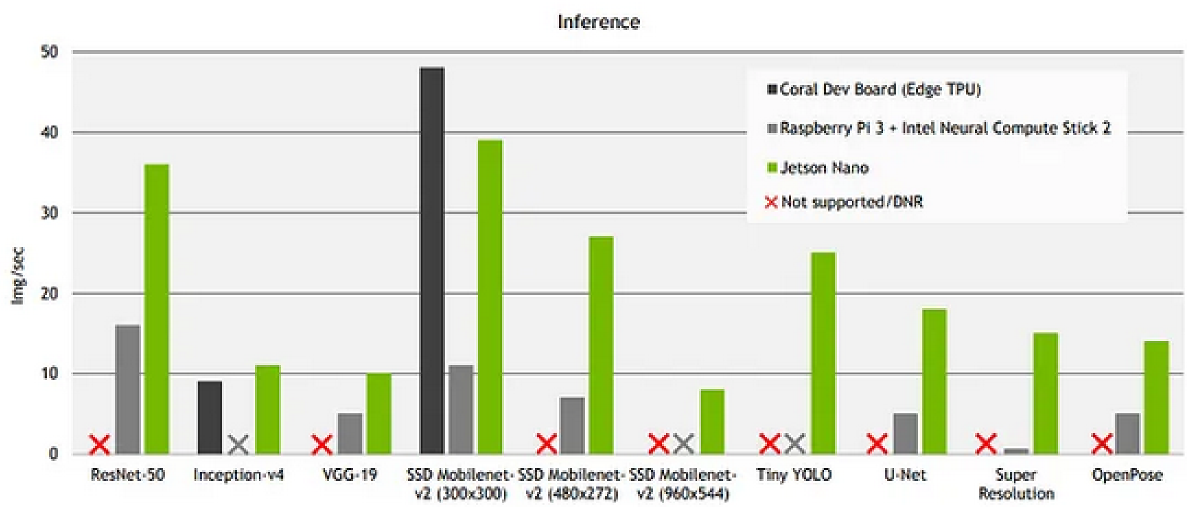

Figure 3.6.1.1.1: Showcase comparison between the Coral Dev Board and the NVIDIA Jetson Nano with different Object Detection Models.

For our purposes the board that has the most appeal is the NVIDIA Jetson Nano. Though it is the largest in size it is still small enough to be implemented within our device. The development kit is priced between both other options and is available. Since the development kit comes with several libraries, which will be utilized when designing and training our algorithm, this also had an influence on our decision. The board also allows for pre-trained models to be loaded onto the development kit which allows for training of the model on another device and transferring it to the board which is something we will utilize when training our own model for our object detection. . Overall, the board seems that it has the best optimization for our intended purposes and the specifications for the board have the most appeal to them. Though the other boards are also decent, one is not obtainable and lacks the ability to load pre-trained models to it and the other doesn't seem to come with enough computing power or number of camera connections that we would need to create our device, thus leaving the NVIDIA Jetson Nano as our best choice and the more desired one in general. Below is an image for each of the connections found on each board to show a better layout of them and to show which board has more options.

The connection schematics were also used to get a better understanding of what is available from each board and what connections are available on the board. This allowed us to have a better breakdown outside of the specifications of each board that aren't just performance related. Using the schematics also helped in picking Nano Jetson board as it has more overall connections and allows for two camera connections, which is what we need for our device as mentioned previously. Though the other boards could also still be implemented with one camera, only utilizing the one within the chamber housing the bees, it would still be beneficial to have both connected to the development kit. One last thing to consider when looking at the boards is that a MicroSD card will be needed as it doesn't come with the kit. Being that we don't know the exact number of images, though it will be more than one hundred and of a higher resolution to ensure that the object is easily identifiable, that we will use it is better for us to get something of a larger storage size. Since the cards are also not expensive, the card we will purchase alongside the kit will be a SanDisk 256GB Ultra MicroSD. This is a large amount of storage for what our purposes are but will allow for extensive testing on the board, which will be needed when training the object detection algorithm.

3.6.2. Microcontrollers

This section will cover the options we considered for the microcontroller (MCU) of our project. For this device, the MCU will have many responsibilities as the internal controller of the device. Each option we have considered will be a MCU rather than a field programmable gate array (FPGA). We choose to use a MCU because of the predefined programmed hardware structure. We do not need to reprogram any of the hardware components included with this board, so using a FPGA would be unnecessary. Further factors to consider in the MCU is that it will ideally provide a low power consumption. This MCU will not be dealing with tasks that need high processing power, like the machine learning algorithm, so having a low consumption MCU is desired. Another factor to consider is the communication protocol. We will be using SPI and I2C protocols. The microcontroller must have a decent amount of general purpose input/output (GPIO) pins. The GPIO pins will help connect the MCU to other peripherals. Another aspect to consider is cost, we want to make the device as affordable as possible.

The first option is the launchpad MSP430G2ET manufactured by Texas Instruments. Our group is familiar with this MCU after using it in a few other classes. It is an ultra low powered microcontroller with a sixteen bit reduced instruction set (RISC) CPU [39]. The MSP430G2ET has the lowest power consumption of any of the MCU we considered with an operating power voltage of 1.8 volts to 3.6 volts. The MSP430G2ET can also operate in different power saving modes to decrease power consumption. The clock for this MCU uses a thirtytwo kHz crystal oscillator, this is a low frequency and power clock. This clock was designed to help maintain the MCU's low power consumption. The MSP430G2ET is a twenty pin MCU with eight GPIO pins that has a universal serial communication interface that supports UART, I2C, and SPI connection. The price for this board is $13.29. This makes the MSP430G2ET the cheapest board with the least amount of GPIO pins.

The second option is the UNO R3 manufactured by Arduino. The operating power of this board is 2.7 volts to 5.5 volts with 512 bytes of SRAM [40]. The cpu is a sixteen bit RISC architecture. The UNO R3 has a total of twenty pins with fourteen pins reserved for GPIO pins. The fourteen GPIO pins are an increase when compared to the MSP430G2ET that has 8 GPIO pins. The UNO R3 also includes a USB 2.0 port for wired connections. This MCU has a sixteen MHz crystal oscillator clock. The board supports UART, I2C, and SPI communication. The price for this board is $27.60. This board option is in-between the MSP430G2ET and Raspberry Pi 4 model b in most categories. It has slightly more to offer than the MSP430G2ET, but less than the Raspberry Pi 4.

The third option is the Raspberry Pi 4 model b manufactured by Raspberry Pi. This MCU has fast commuting, the user can pick to have one, two, four, or eight gigabytes of RAM [41]. The Raspberry Pi 4 also comes with many hardware connections: an ethernet, USB, micro HDMI, and USB-C power supply ports. This board comes with a forty pin GPIO, which may be a bit overkill for this project, and a quad core Cortex-A72 cpu. The clock frequency for this MCU is 1.5 GHz. The operating power is three volts to five volts. This board can use UART, I2C, and SPI communication. The price for this board varies with specifications, at two GB of RAM the MCU is $35 and four GB of RAM is $55. This is by far the fastest computing board option we have looked at, but also the most expensive.

The Raspberry Pi 4 is the most advanced option of the three considered. This MCU is at the top in each category, as demonstrated with the table below. It has the most RAM, GPIO pins, clock frequency, power, and cost. Although it provides all of these benefits it offers more than what we need for the MCU of this project. The other two options are the MSP430G2ET and the UNO R3. To begin with, they both have the same amount of RAM at 512B and SPI controllers. The MSP430G2ET comes in at a lower price, consumes less power, has a slower clock, and has less GPIO pins. The decision ultimately comes down to power consumption, clock speed, and GPIO pins. The MCU selection for this project is the UNO R3. We chose the UNO R3 because we believe that the MSP430G2ET had many of the factors we were looking for but didn't have enough GPIO pins. The eight GPIO pins are not enough to satisfy this project. In terms of power consumption the UNO R3 can be configured to decrease its power consumption with its sleep or stand by modes. This is great for when the device is in an idle state and does not require a large power consumption.

Name	Power (Volts)	RAM	GPIO	Clock frequency	Cost
MSP430G2ET	1.8 - 3.6	512B	8	32 kHz	$13.29
UNO R3	2.7 - 5.5	512B	14	16 MHz	$27.60
Raspberry Pi 4 Model B	3 - 5	2GB	40	1.5 GHZ	$35

Table 3.6.2.1: Device Microcontroller Options.

3.7. Machine-Learning Algorithms

The BEESTING device will involve a lot of different engineering disciplines as well as software. One of the important and most crucial is that the device will utilize machine learning. The machine learning algorithm we narrowed it down to two options which were a Region-Based Convolutional Neural Network (R-CNN), more specifically a faster R-CNN which is just a better version of a base R-CNN and will be discussed later and You Only Look Once (YOLO) which also has other iterations. Our device needs to be able to have reliable object detection within the sensors/cameras at a reasonable speed but more importantly a high accuracy. Since the device will utilize five bees inside of a chamber which when the bees stick their proboscises out, the machine learning algorithm will be able to detect and verify that the bees have stuck the proboscis out then informing the device. To make sure this device is portable an AI development kit will be used to run the algorithm and check whether the bees' proboscises will be used.

3.7.1. Region-Based Convolutional Neural Network

R-CNN has a few different iterations or variations that we looked at. The one that seemed to us to be the most useful and beneficial is the Faster R-CNN. The faster R-CNN is a more advanced version of a Fast R-CNN and has built in features to help it with detection in both speed and accuracy [42]. One of these tools is the RPN (Region Proposal Network) which tells the object detection algorithm where to look. This algorithm also uses what are called anchors or anchor boxes which function as a reference box of a specific scale or aspect ratio. This allows for detection at all different types of scales as they are layered over one another. This structure between the two functions allows for a faster overall computation time within the Faster R-CNN but also allows for a higher degree of accuracy over previous R-CNN iterations [43]. Overall the Faster R-CNN allows for quick and accurate object detection and has a very high reliability but when considering real-time application it falls short as the speed isn't significant enough, especially with more recent algorithms.

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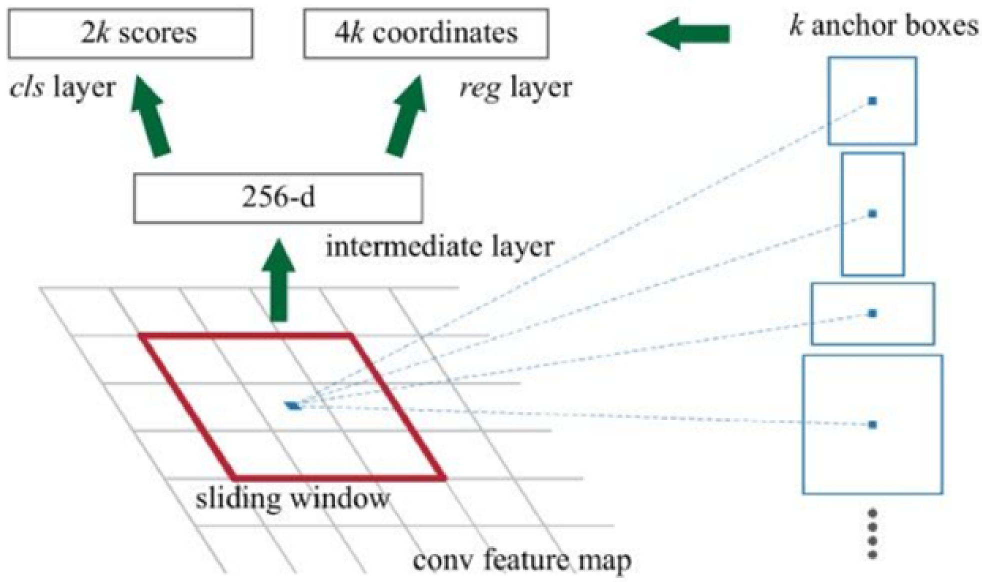

Figure 3.7.1.1: Anchor Boxes and how they're implemented.

3.7.2. You Only Look Once

When looking at which algorithm to use for this project it really boiled down to two different algorithms, the first one being YOLO with its subsequent iterations and a R-CNN which also has other iterations. We spent time looking at both advantages and disadvantages of the algorithms and the conclusion is that YOLOv4 would be the better option. Being that both algorithms have more modern and advanced algorithms than the original, a comparison was made between YOLOv4 and Faster R-CNN [44]. Starting with the YOLO algorithm in general, YOLO provides a faster time for detection with a relatively high level of accuracy when it comes to basic object detection (For things like cars, animals, etc.). Older models of YOLO had issues in the past with detection of smaller objects in the distance but more recent models, like YOLOv4 show a better system that allows for even faster and more accurate detection over a Faster R-CNN [42]. YOLOv4 is also a more recent algorithm that considers and tries to mitigate factors that reduce the accuracy of the algorithm such as the vanishing gradient (creates a difficulty in training the model) and to improve other functions such as feature propagation and reducing the number of network parameters. It also utilizes CSPDarkNet53, based on DenseNet (a type of convolutional neural network designed to also improve the declining accuracy caused by the vanishing gradient), that allows for the application of such features to improve the algorithm as well as reducing bottlenecks [46]. Though the YOLOv4 algorithm is incredibly fast, compared to others, and for the most part falls within a high degree of accuracy it still has disadvantages as well such as struggling with small object detection which is something we must take into consideration. Other iterations of YOLO were also looked at, like YOLOv5, but the algorithm is very similar to version four with and performs at an identical level as its predecessor offering no significant advantages over the previous version [47]. More recent versions were also looked at as well but it is better to implement a more tested and researched algorithm then a cutting edge one for our intended purposes.

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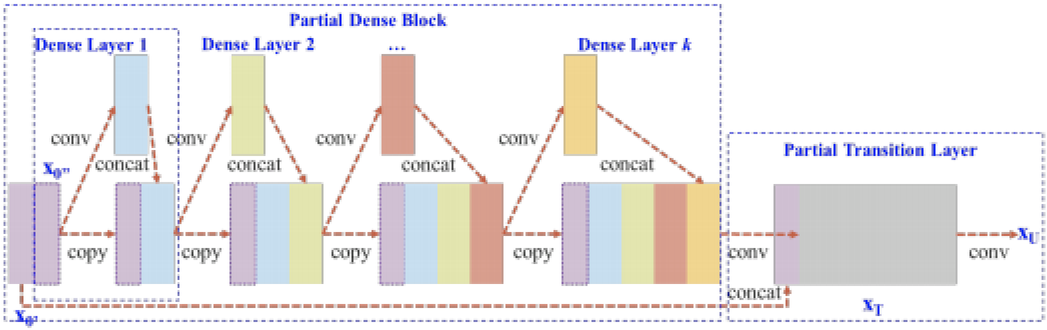


Figure 3.7.2.1: A breakdown of the CSPDarkNet53 and how it works.

3.7.3. Single Shot Detector

Single Shot Detector (SSD) is one other object detection model that maximizes speed and also improves accuracy [48]. SSD also has other variations but the one we considered is SSD300. The number indicates input resolution for the images. This model specifically eliminates region proposal networks, which R-CNN utilizes, to allow faster computation and detection times [49]. This leads to a drop in accuracy though, something we care the most about, but has built in features to compensate for it. For instance, SSD has improvements in multi-scale features and default boxes that can be implemented within our design. Since the camera we plan to utilize isn't going to be high resolution, this particular model can provide for the purposes we need it for. Using lower resolution also further increases the detection speeds within the model allowing for faster detection [50]. Though accuracy is our main consideration, speed is something we also need especially within what is considered the real-time spectrum for object detection. Due to the improvements within this model, it has the ability to outperform even Faster R-CNN in terms of accuracy though only by a small margin. When extracting features, SSD uses VGG16 which works similar to a Convolutional Neural Network which is what will be utilized when looking for our object in question.

3.7.4. Comparison

When considering the important aspects of the algorithms and deciding on which one to choose, certain aspects needed to be considered. The first two aspects that were the biggest factors in choosing which algorithm we are going to use are the speed at which detection is made as well as the level of accuracy that it can detect the object (Specifically smaller objects). The reason for this is that since we are working with bees and the object that we are detecting is the proboscis of the bee (length varying from 6.6mm – 7.8mm), it is important that the algorithm can detect it quickly and with reliable accuracy within the small frame of time that the bee sticks its proboscis out to the time it goes back in. The only other factor of important significance for choosing is the sample size of data that will be needed to train the algorithm for detection. Since we are dealing with an animal's tongue, a large number of images will be needed to train the model which will require not only images that can be found online, but ones that we will compile from the bees.

The most important factor that we looked at when comparing our models was accuracy. For our purposes our system needs to have a high degree of accuracy to ensure that the output does not result in a false positive or false negative. This meant that looking at the accuracy of each model based on a dataset that extensively tested the models gives the best idea of what level of accuracy we can expect for our niche. Faster R-CNN boasts some of the highest accuracy due to its two-shot approach. Though it underperformed within the MS COCO dataset it still provides high degrees of accuracy within its individual uses. YOLO and SSD also have high levels of accuracy and more recent iterations have shown much better improvements in accuracy over Faster R-CNN's two shot method.

The next two important considerations were speed and its ability to detect small objects. Since our device is to have a practical application, it needs to work in real-time. All three models that were considered are able to operate in real-time or at the least approach it. Since our device is supposed to be able to detect explosive chemical traces it is ideal that the response from the object detection model be as fast as possible. Matching that with accuracy, we want to have a model that can maximize accuracy while also ensuring that the speed can still operate within real-time. When looking at the size of the object we're detecting, this can also have an effect on both the accuracy and speed. Though this can be alleviated with a proper camera, we still want to make sure that the model itself can still operate with small object detection in mind.

	YOLOv4	Faster R-CNN	SSD300
Speed (Object Detection Rate)	Can operate at speeds of 60 FPS or greater (end to end, reading video, running the model, and saving the results).	Operates between a range of 20-30 FPS including everything referenced under YOLOv4. Threshold for real-time application is 30 FPS or more.	Ranges from roughly 40-59 FPS depending on the model testing. When tested using the VOC2007 which achieved a speed of 59 FPS
Accuracy/MAP (mean average precision. How often the algorithm is correct in detection/can detect object of interest)	Based on different studies the mAP of YOLOv4 varies from study to study but seems to hover around 80%-90%. When considering the MS COCO dataset, the mAP is about 43% which also varies based on the dataset tested.	For a faster R-CNN the accuracy can be around the same values for that of YOLOv4 when considering the non-standard testing method of the algorithm. When using the MS COCO dataset, the average	When looking at the mAP for SSD300 on the MS COCO dataset the overall accuracy is around 34.9%.

	YOLOv4	Faster R-CNN	SSD300
		mAP is around 21.9%.	
Detection of Small objects	The detection of small objects can sometimes be a struggle for YOLO and can sometimes lead to inaccurate identifications or lack thereof. Though this is something that is also affected by image resolution and quality. This was done based on chip defects with an average defect area size of 0.3 x 0.3 mm.	The detection for small objects within a Faster R-CNN can be superior when speed/real-time application is not a considered factor. Though it allows for more accurate detection at the sake of speed, the amount that is gained in accuracy is not a large margin	Since SDD is similar to YOLO as in they are technically both single shot detectors, it also struggles with small object detection. This can be remedied with the camera we're utilizing.
Training Time	When training YOLOv4 using a custom dataset it can take roughly six hours for about 300 images but this is based on batch sizes, the object of interest, and how many of the object is to be detected within the image.	The training time of a Faster R-CNN can also vary depending on batch sizes but is overall much slower. Speed can be increased but accuracy may suffer due to the increase. The average is about eight hours.	Training time can vary for this particular model but overall can be done with a similar amount of images of YOLO. Slightly longer training time then YOLO but considerably faster then Faster R-CNN
Data size required for training	The standard number of images that provides a decently trained model lies between 300-500 images. For a properly trained model, around 100 images and more might be needed.	The same number of images can be used to train this specific R-CNN model as well, as the more images that are passed to the model the better the model becomes at detection.	Similar to the other models, roughly 150-500 images can be used to train the model.
Date of creation	2015	2020	2016

Table 3.7.3.1: Comparison between the YOLOv4 and Faster R-CNN Neural Network Algorithms.

The results of these tests are taken from multiple sources comparing different iterations of tests and training modules ran through each algorithm to determine some of the factors used to determine efficiency and reliability of the algorithms. Most of these algorithms are tested using the MS COCO dataset as a standard for testing algorithms that compares over 80 object classes to allow for in depth testing of those algorithms. The MS COCO dataset is designed to test an algorithm to its limits which can yield much lower accuracies and speeds as compared to when tests are done with a specific object determined and detecting less objects overall.

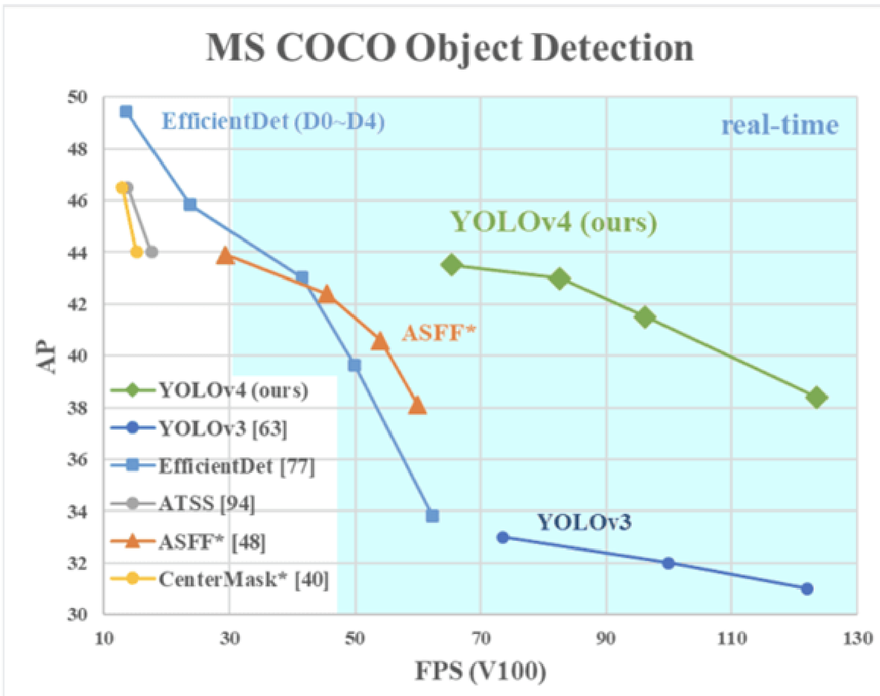


Figure 3.7.3.1: A graph showing the results of the YOLOv4 test utilizing MS COCO dataset compared to other algorithms.

3.8. Software Communication Protocols

3.8.1. Serial Peripheral Interface

Serial Peripheral Interface (SPI) is a communication protocol that uses one master and one or multiple slaves. The single master communicates with one or several devices. The protocol uses a full-duplex system with two data wires and the master generates the clock signal [51]. A full-duplex system means that data can be transmitted in both directions at the same time. The fact that both stations can send and receive data at the same time is a large advantage when compared to other styles that are not able to accomplish this feat. SPI is a synchronous data bus, this allows for the transmitter and receiver clocks to be synced. As stated before the master generates the clock signal and transmits it to the peripherals to remain in sync. SPI uses four wires in total. Two wires are used for the data lines, these are called the peripheral in/controller out (PICO) and the peripheral out/controller in (POCI). Another wire is for the clock signal called the serial clock (SCK). and the last is for the chip select signal (CS) [52]. The terminology of these wires may differ from one manufacturer to another. The SCK line is used to communicate with peripherals the clock signal generated by the master. The PICO and POCI wires are used to transmit data. The PICO transmits data from the master or controller to a peripheral. The POCI is used if the peripheral needs to send a response to the master. The chip select signal line is used to select which peripheral the master is communicating with. The signal lets the peripheral know that it should be ready to receive data. To allow the master to communicate with multiple peripherals, each peripheral must have a different chip select line. For the other three lines, they can either be the same or use a daisy chain. A daisy chain will have the data in line of one peripheral go to the data out line for another peripheral.

3.8.2. Universal Asynchronous Receiver/Transmitter

Another communication protocol is the universal asynchronous receiver/transmitter (UART) [52]. UART is a protocol used to communicate and send data between two devices. Being one of the earliest forms of data communication and transmission, UART has lost popularity through the years to new protocols. However, UART still remains one of the more simple and cost effective methods. UART uses two wires to transmit and receive data. UART supports simplex, half-duplex, or full duplex systems. Simplex data transmission means that data can only be sent in one direction. Half-duplex transmission is when data can be transmitted and received from both ends, but not simultaneously. A receiver or transmitter can not send data if the other end is already sending data. As stated above in the SPI section, a full-duplex can send data both ways simultaneously. This allows the UART protocol to be more flexible and cover a variety of devices. UART is asynchronous. This means that the transmitter and receiver do not share a clock signal. This further increases UART's flexibility and usability in many different systems. A concern when using an asynchronous system is the need for a signal bit. The transmitter needs to send a start bit to the receiver, to tell the receiver that it should be ready to receive data. This also means that a stop bit is needed as well. This lets the receiver know that the data is over. A common problem with this is data loss. In some cases the receiver may incorrectly identify a start or stop bit and this will lead to error in the system. To help prevent this, parity bits are used. Parity bits let the receiver know how many ones are in each frame based on whether there should be an even number or odd number of ones. A parity bit is completely optional. Overall, UART is still a widely used simple data protocol used today in many embedded systems.

3.8.3. Inter-Integrated Circuit

Inter-integrated circuit (I2C) is a communication protocol that uses techniques and methods from both SPI and UART [53]. Like UART, I2C only uses two wires to transmit data. These two wires are called the serial data (SDA) and serial clock (SCL). Data is sent and received through the SDA wire, while the SCL wire controls the clock signal. I2C is synchronous, similar to SPI. This means that the clock signal is synced throughout the system. Thus I2C does not need the start and stop bit in the SDA line like UART. Instead I2C has a start and stop condition. The start condition occurs when a master sets the SDA line to low voltage. This allows for the master and slave to get ready to transmit data. The stop condition is when the SDA line is set back to high voltage. Another similarity that I2C has to SPI is the use of master and slaves. In SPI, the system has one master communicating with multiple slaves. I2C takes this technique one step further, I2C allows for multiple masters and slaves. The support for multiple masters allows for systems to have multiple controllers to transmit to different peripherals at the same time. This will increase the speed of the system. The problem with multiple masters is when two or more masters try to transmit data to a slave at the same time. The SDA wire can not transmit all the data. This problem is solved by having the master detect if the SDA wire of the slave they are transmitting to has a high voltage or low voltage. A low voltage line means that the SDA wire is in use and the master will have to wait till the SDA wire is set to high voltage. Furthermore, I2C is a half-duplex system. Data can be transmitted from both ends at different times, not simultaneously. All in all, I2C is a more complex protocol than SPI or UART, but supports the use of multiple masters and slaves.

3.8.4. Universal Serial Bus

Universal serial bus (USB) is a common communication protocol. USB is known for its reliability and ease of use [54]. This communication protocol is very common with memory sticks, hard drives, and exterior peripherals. There are many computers today that support USB ports. A USB network is made up of a host, hubs, ports, functions, and devices. The areas we will discuss are the host, port and device. In this project the host will be the microcontroller with the object detection. The microcontroller and camera will have a port to connect each other with a wired connection. Each device will have a defined USB protocol to transfer data. Each port will consist of several Tx and Rx lines. The Tx lines are used to transmit data and the Rx lines are to receive data. The data is transferred on these lines in four different types of data packets depending on what the data is. These packets consist of a token, data, handshake, and start of frame packet. Token packets are data sent only from the host. Data packets are data sent from the host or peripherals and are typically followed by a handshake packet, which is an acknowledgement sent from the receiver to the transmitter after a data packet. A start of frame packet is used to specify the start of a new frame. In this project, data transfer and communication will use a token packet, data packet, handshake packet. The first packet in data transfer is a token packet, this will specify to the receiver what data will be transferred. The next part of the data is the data packet that carries the data and the final part of the data transfer will be the handshake packet. This final packet will let the transmitter know that it has received the data.

3.8.5. Software Communication Comparison

The most important factors to consider when selecting which communication protocol to use is the speed, clock signal, and complexity. We want the quickest and most simple protocol. The more simple protocols are UART and USB, while SPI and I2C are a bit more complex. The fastest protocol is SPI. When selecting what protocol to use, we looked at the events that were to take place for each peripheral. We decided to use SPI in most cases because of the speed of the protocol and I2C in communication between microcontrollers. Using I2C for the communication between the microcontrollers will allow us to use the faster clock of the NVIDIA Jetson Nano for the camera sub-system.

4. Project Standards and Design

4.1. Biological Standards

4.1.1. Choosing a Bee

As the name implies, the most important aspect of a bee-based sensor is the bees themselves. With over twenty thousand types of bees in the world, one particular species stands out. This species is known as *Apis Mellifera*, commonly referred to as the European honeybee. These bees are used on a global scale for pollination projects, honey production, and agriculture, making them affordable and readily available. Since these bees will be hand collected, it is important to note their identifying physical features. Honeybees are reddish-brown with black and yellow rings on the abdomen. They have an abundance of hair on their thorax, and a minimal amount of hair on the abdomen. All of these bees should be extracted from the same hive. If not, the insects can become agitated by the presence of the other bees, and even hostile to them. Placing the bees under undue stress is not only needlessly unethical, but also decreases their work efficiency.

4.1.2. Collection and Selection

The hive we will collect from is at the experimental ponds near the Robinson Observatory, on the campus of the University of Central Florida. We will be accompanied by members of the Apiology group and will use specially designed bug nets to avoid harming the insects. Once there, we will aim to catch between twenty and thirty bees. Though this is a small number, it is important to avoid disrupting the colony's natural processes by removing too many bees at once. The process of capturing insects can also be time consuming, so limiting the project to thirty bees at once will be key to efficiency.

Once the bees have been separated from the colony, they are chilled in a refrigerator to decrease their metabolism, calm them down, and decrease agitation. When their movements slow to a near standstill, they are carefully placed into a harness. The harness will wrap around the bees and bind them to a cartridge that is compatible with the BEESTING device. The bees will live in this harness for the remainder of the training and use process.

(Permission Pending)

Figure 4.1.2.1: A group of harnessed bees ready to be loaded into a detection device.

After the bees are harnessed, they must pass a test to determine if they are suitable to be biosensors. All bees have an appendage called a proboscis, a long and tongue-like tube that is used for eating and gathering nectar. The ability to extend the proboscis, otherwise known as the proboscis extension reflex, is essential to the device. To test if the bees have this reflex, a cotton swab with sugar water on it will be placed in front of them. If a bee extends its proboscis to taste the reward, it passes to the next phase of training. If not, it will be released back to its hive.

4.1.3. The Pavlovian Response and Bee Intelligence

The next part of training involves repeated exposure to a specific scent, immediately followed by a reward. For six seconds, bees are exposed to a vapor with similar scent properties to an illegal substance. During the last three seconds, they are given a reward of sugar water. This is a common technique used to train animals, and has been previously used in the training of dogs. By associating the scent with the reward, the bees are conditioned. They learn to extend their proboscis whenever they encounter the scent, anticipating the subsequent reward of sugar water. With the conditioning process, the bee establishes a reliable connection between the scent and the desired behavior. This connection will become stronger as the process repeats. After several hours, the bees are evaluated, and if they extend the proboscis without a reward, they are considered fully trained and ready to use in a detector.

The type of conditioning utilized for this project is classical conditioning, also known as the Pavlovian response. It was developed by Ivan Pavlov in the early twentieth century, and uses the brain's reward mechanism to 'hard-wire' a response from the target subject. The original experiment supplied dogs with food while a bell rang. Eventually, the ringing of the bell made the dogs salivate, even when no food was present. This technique works on bees because of their high intelligence. Honeybees have sophisticated social structures and are able to teach each other how to solve problems. They can easily figure out the connection between the scent and the sugar water, meaning they will respond to the stimuli in the same manner every time.

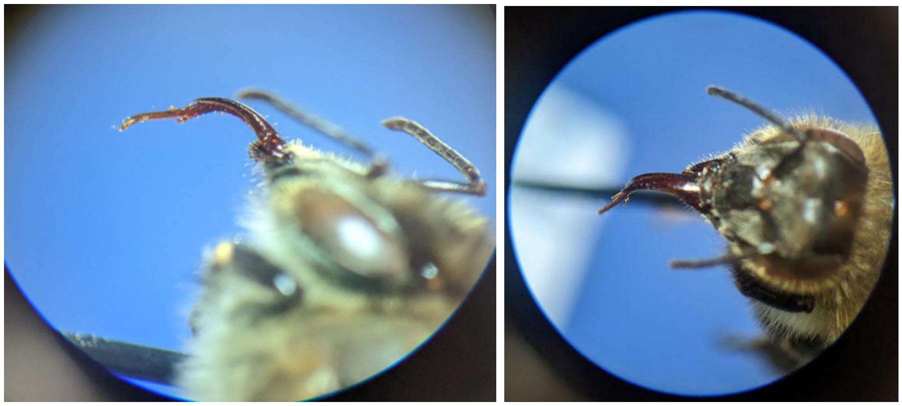


Figure 4.1.3.1: A view of the proboscis under a microscope

The process of training the bees is relatively easy and does not require a large amount of resources or time. All the bees need to survive is the sugar water. They can be left in the harness for multiple days while they are being trained and used in the device. They do not require much attention or care, and as long as the hive they are sourced from is kept healthy, the supply of bees will last indefinitely.

To be qualified to train bees, a person should take a course at a reputable apiary, and ideally have additional beekeeping experience. The job of the bee training technician would involve gathering healthy bees from a hive, harnessing them, refrigerating them, and observing their responses to sugar water and scents. The most difficult aspect of this job would be hand-harnessing each bee. This would require the careful use of tweezers to hold the bee while securing the harness. If the bee stings the technician, it will die shortly after and cannot be used in the BEESTING device.

4.1.4. Alternative Training Methods

Since the year 2006, honeybees have been used for a wide variety of sensing tasks, meaning there have been many variations of training techniques, harnessing, and sensor types. The original method of training did not utilize proboscis extension. Rather, bees were placed in a clear container and conditioned to exhibit ‘avoidant behavior,’namely loud buzzing and frantic movements. The unspecific nature of ‘avoidant behavior’ is why we are not using this method. There is not a simple and predictable motion for the optics to pick up.

Some commercial sensors use specialized machinery to harness bees. They are placed in a container with tubes attached to a wall. The wall is slowly pushed in, forcing the bees into the tubes. The harnesses are then locked when the bee reaches the end of the tube. Because the BEESTING device does not require hundreds of bees, the cost of specialized harnessing equipment would be an unnecessary expense.

Free range detection is an alternative sensing method used by Montana University. This method trains large amounts of bees, then releases them over a field where explosives may be planted. The bees swarm to the scent they were trained to, and the swarm patterns were recorded with a

LIDAR system into a density map. This method of detection is extremely expensive, requiring large amounts of bees, insect-safe transportation, and aerial optical systems.

4.1.5. Autonomous Training

As stated, bees display a high level of intelligence and social sophistication. They are capable of recognizing faces, navigating with landmarks, and are even able to play, all of which have been proved experimentally. Bees are eusocial insects that organize themselves into jobs based on age, with the exception of the queen who lays the colony's eggs. Though the signal to start a new job is determined through hormonal changes, many jobs require additional communication between bees to be completed. When collecting nectar, bees will use dances to convey the location of flowers. They can teach each other the directions to get there, and this teaching/learning ability can be extended to nearly any simple skill. Bees have taught each other tasks in a laboratory for sugar water rewards, and even communicated how to play with rolling balls.

With proper incentivisation, bees may be able to train themselves to extend their proboscis. The same reward system can be applied where sugar water is provided after scent exposure, but on a larger scale. As this behavior is reinforced among a generation, the older bees should start teaching the behavior to younger ones.

4.1.6. Animal Protection Laws

The Animal Welfare Act, passed in the year of 1966 and amended numerous times, regulates the treatment of animals in laboratories. Under the most recent version of the law, all warmblooded animals aside from mice, birds, and rats are protected from undue pain and poor living conditions. Though honeybees are intelligent creatures, their insect status stops these protections from extending to them. Under Florida law, honeybees can even be eradicated en masse by a certified pest control operator. This lack of protections around bees means that no special precautions must be taken to ensure the legality of the BEESTING.

There is, however, an ethical concern. Since many invertebrates exhibit emotions and may be able to feel pain, scientists are hesitant to perform potentially distressing experiments on them. Many countries even have protections for cephalopods, the group containing octopuses and squid, because they are highly intelligent and even meet the criteria for sentience. This project takes these ethical concerns into account. All bees will be sourced from the same hive to prevent agitation. They will be used for only a short period of time, and returned to their habitat when done. They will also be marked so that repeated use of a bee does not occur.

4.2. Hardware Standards and Constraints

4.2.1. Connection Standards

Connection standards are something that we have to ensure to follow. Being that our device is utilizing many different components, we need to ensure that the proper connections between the devices and components can be made and function properly. For the camera and the AI development board, to ensure compatibility the camera's cord was taken into account and cross checked with the development boards to ensure that a connection between the two can be done. We also need to take into account the connection made between the microcontroller and the numerous IR sensors that will be implemented in the alternative chamber to ensure proper feedback. The battery that will power the system will also need to be able to connect and supply power to each hardware component within the system. This meant we also needed to not only keep track of how much power each component needs but the type of port that is required to power the board to ensure it can be implemented with our power supply. Connections also need to be considered and standardized for both the LCD display and LEDs.

To ensure that these standards are followed as well for the PCB design we will be following IPC standards for the connections within our PCB. IPC-2221 is a generic standard for PCB design that will be followed to ensure proper quality and performance from our PCB design. This particular standard also has other underlying standards further within the IPC-2220 series of standards that cover rigid, flex, and other PCB designs which we will also utilize for our particular design to follow the standards for our PCB.

In this project we will be using a USB 3.0 connection between our camera and the Nvidia Jetson Nano. This is a USB-A type connector. USB standards have gone through several revisions over the years. These revisions are maintained and supervised by the USB Implementers Forum, Inc. The standards state the size and connections each port must maintain to properly work. These standards are in place to ensure that the connections are supported correctly and keep connection speeds high.

4.2.2. Soldering Standards

J-STD-001[55] is the standard issued by the Institute for Printed Circuits (IPC) for soldering. The IPC first released this standard in 1992 and has since published revisions to the standard. The IPC issued this standard to help train and certify individuals on a proper and safe process to connect two metal surfaces. This standard goes into depth on the material requirements, process, and acceptable outcomes. Material requirements cover the type of solder paste, solder system, cleaning media, and flux to name a few. It is important to use the correct material, so no errors or defects may occur during the process of soldering. Speaking of process, the standard states the proper way to solder from the distance between two mounting parts to the method used for through-hole components. The standard goes on to demonstrate how a soldered part should look and if any errors or defects occurred, the standard tells one how to fix it. Improper soldering is a quick way to ruin a project or inflict injuries. In this project, we will be following this standard to avoid common problems found with incorrect soldering. Ultimately, J-STD-001 is an essential standard to follow the best practices in soldering.

4.2.3. Battery Standards

It is important to follow certain battery standards in any project that utilizes a battery. Improper use of batteries may cause damage to electrical components and the design of this project or may cause bodily harm. Batteries have a wide variety of standards that are in place to increase safety and compatibility. In this project, we will be using a lithium battery. To find the correct standards we looked into standards published by the International Electrotechnical Commission (IEC). The IEC is an international organization that publishes and issues standards for electronic technologies. The standards that we found and will need to follow are the IEC 61959:2004 [56] and UL 1642. These standards state the safety requirements and testing that each lithium battery must maintain and will be used in this project. Following these standards will ensure that the system is protected from hazards that may occur when using a lithium battery.

We will also follow standard safety procedures when storing, charging, and testing the battery. This is in accordance with UL 2054, which ensures proper handling of both non rechargeable and rechargeable batteries. Since the battery we're considering is relatively powerful we also need to ensure that the battery remains undamaged and is stored properly. We will also utilize the proper charger for the battery so that it doesn't lead to any harm. To keep in check with safety the battery will also have proper ventilation within the system so that during times of discharging the battery does not reach unsafe temperatures that can lead to catastrophic battery failure. The battery will be tested thoroughly to ensure that the output of the battery is correct. It will also be tested to ensure that it works with the components of our device and that it is able to power everything before final implementation of the BEESTING device. Following this the PCB itself will be tested to ensure that no short circuits occur within to protect the battery from possible damage.

We also want to ensure that the battery that we implement follows some level of reliability standards. Most rechargeable batteries can withstand heavy use without failing. In terms of the battery itself, we are obtaining it from an outside source meaning that reliability will not be entirely on us but storing it correctly and making sure that it's properly charged will allow us to keep our battery within proper reliability. This also means properly charging the battery which is already a safety standard which will contribute to the reliability to the battery and to the overall device.

4.2.4. Economic Constraints

This section will cover the economic constraints for this project. Economic constraints are economic restrictions or limitations placed on this project. We plan to create a device that is low cost and can be mass produced for our target audience. One of the many constraints for this project includes creating a device as cheap as possible while still maintaining an effective design. To create an effective device that is available to many users, we will limit the cost to manufacture the device. The cost should be no more than five hundred dollars to build a single unit. Keeping the cost of the device low would allow us to make the maximum amount of profit. We want our project to be priced higher than the total cost to manufacture it. On the other hand if the price of the device is too expensive, then consumers will be hesitant to purchase the device. This will decrease the overall demand for the device and decrease the profit we would be able to make. Therefore, maintaining a low cost design will help us achieve the maximum profit that we can from our device.

4.2.5. Weight and Size Constraint

Since one of our Engineering requirements is that our device must be less than fifteen pounds, this creates a constraint for us as well. We want the BEESTING device to be handheld with two handed operation. To ensure this we have to take into consideration each component and roughly how much weight they will add. Size also has to be considered so that the device is not bulky and can still be handheld by the user. This required us to ensure that the size of the AI development board and the microcontroller can be integrated into our design. When choosing our components we made sure to record the size of each one and determine how each one would affect the overall design. Luckily the size for the major board components has only slight variations which can be accounted for in the overall design and can be fit within a space inside of our design. Taking into consideration weight from these components as well does not add significant poundage to the design of the BEESTING and falls within parameters. Another way we are reducing weight is to 3D print the frame and body of the device. This will allow us to have more control over the shape of our device and to properly ensure that our design can be reduced weight wise as much as possible.

The weight and size is also dependent on the materials we use for printing the housing of the BEESTING device. We want our device to be handheld and operated with two hands. This means the individual components within the device as well as the housing of the device should be lightweight and have the ability to be used by anyone within its specific use case. As an aside the device should also be durable which adds to the consideration for the materials used for printing the device. This also means minimizing designs that require thick sections within the housing unit and creating more negative/empty space within the housing unit without limiting functionality to create the most weight efficient device for the user.

4.2.6. Manufacturing Constraints

Manufacturing constraints include the material availability. This is an important factor to consider in a project such as this. Similar to any product, the materials to build this device must be available. Without any of the correct material, the device can not be constructed. For example, the chassis and chambers for the device are to be 3-D printed. Without the correct and proper filament, the device will not operate the way it was designed to. This is a major issue because this will decrease the value of our product. In addition any shortage of material will hinder the construction of the device. If the manufacturer were to run out of material then production would halt. This would create bad feedback from consumers on how long it takes to build our device. To avoid these problems, we will be using popular and common material that can be obtained in abundance and is readily available.

One other issue is that this device utilizes bees as a crucial component. Because of that, manufacturing of the device and mass use might not exactly be practical. This is in part for several reasons, first being that someone qualified to handle bees would be needed during times of switching out bees from the chambers. For instance a beekeeper would need to be readily available for handling bees within the chamber in case of an issue with the device itself. Secondly, since bees have a short training time and a short retention time for training, this will require the bees to be switched out from the loading trays on a regular basis of about every other day. This means having a beekeeper that's also handled to remove the bees from the device and replace them with newly trained ones. Though autonomous training is possible with the bees, they will still forget at some point and will need to be trained all over again. For mass manufacturing purposes and use this will also require a large number of bees to be trained if it were to see mass use. Once again this would require a large number of beekeepers to ensure mass use.

4.2.7. Temperature Constraints

Since this device is utilizing a Lithium Ion battery and several hardware components, temperature must be monitored and tracked at all stages of prototyping, testing, and final implementation. Temperature overall is not just being considered for the operation of the hardware components either, the bee's must be kept in an environment that does not exceed a certain temperature threshold. If this occurs and the bees internal temperature rises to 42℃ this will result in death of the bees, something we want to avoid entirely. We have no way to monitor the internal temperature of the bees so we will monitor the temperature of the chambers the bees are housed in to avoid reaching a temperature fatal to the bees. Temperature also needs to be monitored and controlled for the hardware components.

Since all hardware components, including the NVIDIA Jetson Nano, will throw off considerable heat within the device, temperature must be monitored and kept to a minimum to avoid overheating the components as well as the chambers. Ideally we want to keep the temperature of our hardware components below the same temperature that the bees would experience heat death at. This will be accomplished through design of the device itself and how airflow will be pulled into the device. The hardware components themselves should be able to operate at temperatures that go up to their maximum. With that considered, temperature will be held to strict constraints within the chamber while hardware components will have more leniency with the temperature constraints only if temperatures affect the temperature within the chambers.

4.3. Software Standards and Constraints

4.3.1. Programming Languages

This section will go over the standards and constraints in programming languages. Programming languages have standardized syntax for reliability, security, and portability. To further explain, programming languages use standardized syntax to keep consistency in each system. If each system used different programming language standards, then systems would not be able to collaborate and cause massive errors to occur.

Similar to any software program there are natural constraints to create the most efficient code. Every programmer wants to develop the quickest and most accurate code while also maintaining clean code. Clean code helps programmers easily troubleshoot bugs and create efficient code. This includes having optimal loops, omitting useless or unnecessary lines, and using correct and updated syntax. Our code should include as little loops as possible to decrease the runtime of the code. To further explain, loops may take an extremely long time based on how long it takes for the conditions to be met. By programming loops to not include that extra time, the programmer can reduce the overall runtime of the system. Since a requirement for this project is to have a response time less than one minute, a great way to achieve this is to limit the amount of loops used or optimize the loops. Another constraint is to not include any unnecessary lines of code. This only increases the runtime and creates bugs in your program. In addition, every programmer must follow the proper syntax for the language that they will be utilizing. Below will talk about the syntax and standards that each programmer must follow.

4.3.1.1. C language

A common language used in many MCUs is C. Many MCUs use C based languages for its high performance and wide range of libraries. The most common standardized syntax versions for C are ANSI C, C99, C11, and C17. C17 or ISO/IEC 9899:2018 [57] is the most recent and updated standard for C. ISO/IEC 9899:2018 was developed in 2017 and published in 2018. It is important to follow these standards to keep programming clean and readable for many different integrated development environments (IDE) and compilers. Improper use of syntax and standards will cause bugs within the program or in many cases the program may not even compile. By not using the correct syntax the compiler or IDE will not recognize and execute the program. This is obviously a major problem. Luckily many IDEs and compilers can pick up which lines have incorrect syntax and help guide programmers in the right direction. This can only be achieved because there are standards for each programming language.

4.3.1.2. Python Standards and Constraints

Python will be used for programming the machine learning algorithms used in this project. The most recent and updated python programming standard is PEP-8 [58]. PEP-8 was first published in 2001 and is still active today. PEP-8 provides guidelines and standard libraries for python that programmers should follow to make python readable to IDEs and compilers. Utilizing these standards will allow for properly optimized code to ensure easy readability and communication between subsystems, such as between the AI development board and Microcontroller.

Following the standard for python will also implement some constraints that come from the standards as well as general constraints for the object detection model. When following the PEP-8 standard, certain constraints/standards within will be adhered to. For instance, the code will follow standard comment standards as well as spacing and line standards. Lines of code will not pass over seventy-nine characters for easier readability for both the programmer and reviewer of the code. Indentation standards will also be adhered to as well so code is blocked properly and segmented in a manner that isolates code blocks for particular purposes. One other constraint will be following a particular training structure. This will require using PyTorch's iterable designed dataset which allows for user-defined iterables. This requires disabling automatic batching and to some extent batching out more specific data. Another constraint will also be placed on the activation function. Since a lot of activation functions exist for training a model, a limit to what is used for training will be applied. Activation functions like the Gaussian Error Linear Unit, and ReLU and its variations. Optimization algorithms for efficiency will also be kept within a range without trying each one for training.

4.3.2. Communication Standards

Similar to the coding languages discussed above, all communication protocols must follow standards. In this project we will be using serial peripheral interface (SPI) to transmit data and communicate with peripherals. SPI uses four wires to communicate, this is different from other popular communication protocols that use only two wires. The four wires are the PICO, POCI, SCK, and the CS. While programming this communication protocol, we must use the correct syntax and wires to transmit data. If the syntax is incorrect, then the communication will not occur. In addition, SPI uses a synchronous clock. This means that the master must generate the clock signal, any other clock signal would be invalid and cause errors in the system. It is important to follow these rules and standards to create clean and effective communication.

One of our engineering requirements is to build a system with a response time less than one minute. To help achieve this requirement we have a constraint on the communication of our system. Serial peripheral interface (SPI) is the fastest communication protocol that we have considered, so to achieve a quicker response time we will be using SPI where we can. In this project we will be using SPI, inter-integrated circuit (I2C), and universal serial bus (USB) to communicate with the peripherals in the device. This creates a constraint of minimizing the use of I2C and USB communication. Although these protocols are fast compared to other protocols, they are slower than SPI. We will use the I2C protocol in the communication between the UNO R3 and NVIDIA Jetson Nano. This is because SPI protocol supports only one master that generates the clock signal, while I2C allows multiple masters. Using I2C allows us to use the clock on the NVIDIA Jetson Nano, which is faster than the UNO R3, for the camera system. Lastly, these communication constraints will help create a faster system and satisfy our engineering requirements.

4.4. Safety Constraints and Ethical Constraints

The BEESTING device has many different considerations and a biological element that can cause overall issues if things go awry. For instance one of our team members and authors of the document is allergic to bees. The primary component of this project is bees wherein our entire detection system relies on them. With that being said we have to consider major safety constraints. This means handling the bees with care and having someone qualified to handle the bees when switching them out for testing. This will also require that one of the authors on the doc to either not be present during this time or to wear a bee suit when testing. One other consideration is to ensure that they carry an epi pen with them during all times when in contact or working around the bees. This is to account for the possibility of a bee sting occurring.

This also requires that the bees be restrained within the device, not only so our system can function but so that the bees cannot escape from the device during operation or when chambers are removed to replace bees inside them. Since this device also will be demonstrated during Senior Design 2 we must ensure that the bees are properly housed and sedated before being implemented into the device, this means ensuring that the bees are calm and not agitated. Safety also needs to be followed so that the bees are not harmed during the use of the device as well when securing the bees. We will also be using during our demonstration and testing of the device, traces of an explosive chemical, though the amount will be miniscule and not active, we want to ensure that proper safety with handling will occur when testing and demonstrations are done. This also requires sedating bees during times when switching them out from the chambers. This will be done by the people handling the bees on our behalf but is something we need for consideration.

Since the bees need to be restrained this also has some ethical elements to it. Though bees are not seen directly as animals, we will still treat them with care as they are the pollinators of our world. To ensure that we are careful when handling the bees, the restraints that we will use will not harm the bees in any capacity. This will require working with Dr. Bohlen so that the bees are secured safely and are not harmed during restraining. As mentioned in temperature constraints, we also want to ensure that the bees do not die due to excessive temperatures. Once again this is to keep the bees safe and to ensure that at no stage are they endangered. This also means keeping humidity within the device to a minimum as this could also harm the bees and lead to death if not carefully kept track of. This also requires us to minimize the time the bees spend inside the device and chambers. They should not be kept inside the housing chambers for more than a few hours during testing. This will require us to change the bees out or removing the current ones and utilizing them on a later date, to guarantee safety for the bees and to adhere to possible safety requirements that Dr. Bohlen might ask of us, which will be followed.

5. ChatGPT and Similar Algorithms

5.1. ChatGPT

ChatGPT is an artificial intelligence (AI) chatbot that was developed by OpenAI and first launched on November 30th, 2022 [59]. Since the launch of ChatGPT, the platform has hit the ground running, gaining millions of users within weeks of operation. ChatGPT is a chatbot that interacts and responds to users. This chatbot can naturally communicate to users, answer questions, fix grammar, summarize texts, and even help bug fix certain code. ChatGPT uses a generative AI model trained with Reinforcement Learning from Human Feedback (RLHF).

To start, generative AI is AI built to receive some kind of media input, like text or images, and reply with a response. Generative AI picks up on data patterns that it learns from a user's input to help train the model. This is where RLHF comes in; RLHF is a training method that uses human feedback and interaction to "reward" the model. When the model outputs a desired response a user or tester will let the model know that the response was correct. This helps optimize responses given by the model. An advantage to using this platform is the system's ability to understand and have a text conversation with individuals as if it is natural, unlike other AI chatbots. Another advantage is the ability to adapt to the user's input to help determine the user's intent in a question, this provides quicker and more efficient answers to user questions.

ChatGPT is not the first of its kind, there have been multiple attempts in the past at an AI chatbot like ChatGPT. These attempts have had difficulty with users training the model to be offensive or give incorrect responses. Unlike past attempts, ChatGPT uses OpenAI's GPT-3 to help control incorrect or undesired outputs from the model. Although ChatGPT has done well not to fall into the same errors as past attempts from other delevopers; this does not mean that ChatGPT has had a smooth introduction. The platform has had its fair share of problems. Within the first week, ChatGPT exceeded the amount of users that the platform can operate with, this caused OpenAI to expand their systems to fit the platform's capacity for users. Also the program can not correctly answer many questions that have taken place after 2021. Ultimately, in the short time ChatGPT has been released to the public it has considerably pushed generative AI further into the limelight to help achieve a new age of technology.

Pros	Cons
Verbose and detailed responses	Not always accurate, can be wrong
Always improving and advancing its software	Limited knowledge from 2021 and after
Adapt to the user's preferences	Some options require money
Versatile and user-friendly	May reduced human workforce in certain fields, causing many to lose jobs
	Security Threats

5.2. Similar Algorithms

Below are three similar platforms to ChatGPT. In each section, we describe a different platform and how it compares to ChatGPT.

5.2.1. DALL·E2

Another AI platform developed by OpenAI is the DALL·E2 [60]. This platform uses generative AI to display images. The system takes text and creates realistic images based on the input.

Similarly to ChatGPT, DALL·E2 was trained using deep learning methods, language processing, and machine learning algorithms to help achieve what it is today. DALL·E2 is helping many companies and businesses worldwide achieve greater value and sales with it's quick image generation and capabilities. The system can help many users find what they are looking for by generating many different perspectives of the same image. DALL·E2 can not always accurately depict what the user desires. The platform is still in its early stages and may not provide images that accurately represent what the user was exactly trying to achieve.

5.2.2. Codewhisper

Codewhisper was developed by Amazon to be an alternative to ChatGPT. Amazon's Codewhisper uses machine learning algorithms to help solve and understand coding problems. The platform provides advice to developers to avoid bugs and gives in-depth responses to fix bugs that may occur. This system could help developers increase efficiency and range. It also integrates well with popular coding platforms like GitHub. Like ChatGPT, Codewhisper's knowledge is limited and can not answer every bug or question you may throw at it.

5.2.3. Bing AI

After the success of ChatGPT, Microsoft incorporated AI into the search engine of Bing. This new system called Bing AI [64] expands the normal search engines capabilities. By utilizing the same technology as ChatGPT, Bing AI generates more natural and verbose responses to its users. Bing AI uses OpenAI's GPT-4 for its generative AI model and machine learning algorithms. With the use of this generative AI model the Bing search engine can allow for more personalized results based on the user. The system can learn from the user's past searches to provide more accurate search responses to what the user is trying to find. Although, Bing AI is not one hundred percent accurate like many of the other options. The AI can mislead you with false information or steer you further from what you are trying to find.

5.3. Beneficial Examples

Some benefits these platforms can provide to students in Senior Design is to provide aid in writing, coding, and brainstorming ideas. One of the tools in ChatGPT is that the system can check a user's grammar. The user submits to the chatbot with an essay or paragraph to proofread and the user will receive a response. The response will demonstrate a corrected text, according to ChatGPT, for the user and provide the mistakes it found and how to correct them. ChatGPT proofreading corrects errors in grammar, formatting, punctuation, and spelling. But does not fix errors in sentence structure. ChatGPT can also help solve bugs that a user may find with their code. By providing the chatbot with code, a student can get advice from the platform on how to avoid the bug or provide a solution to it. This feature is not perfect, but may help guide students to the correct solution. Lastly, another benefit for students is the fact that they can ask ChatGPT for related information or where to find it. This may be a good alternative, if the student is stuck, to help find where to start their project or assignment by giving the student feedback and ideas.

As mentioned before ChatGPT is a strong tool especially when dealing with programming software of most types with specific languages. Considering this, usage of ChatGPT for helping to develop object detection models can be quite effective within standard uses or even niche ones. ChatGPT is a machine learning algorithm and though it is a different type of learning model, it still can be quite useful when developing and producing pseudo code for development of other types of models. This for example could be particularly useful in our case as we are utilizing an object detection model and training it based on our own parameters. These parameters can be passed to ChatGPT for clarifications purposes or to help iron out a possible issue that is going undetected within our code. It could also be utilized to provide the proper steps in training our dataset or utilizing certain tools/functions that exist within machine learning and model training.

5.4. Harmful Examples

One of the largest harmful examples that ChatGPT can yield to a student is plagiarism. ChatGPT supplies its users with verbose and detailed explanations that students may just copy and paste onto their assignments or reports. Students may also copy the code that ChatGPT gives as a response. Plagiarism is very serious and can get a student into huge trouble. The best thing to do for a student is to avoid copy and pasting from ChatGPT. Another negative example for students is that ChatGPT may mislead students with false information. ChatGPT is not perfect and will give users incorrect responses at some point. So relying on ChatGPT to have every answer and not doing the work yourself can be very detrimental. As a student it is best to not fall for these harmful experiences one may encounter.

Elaborating further with ChatGPT and its possible problems that it can cause, ChatGPT is at foremost a tool that can be utilized by both students and workers within industries as long as they understand what they ask from it and its degree of accuracy. This means that when asking it for help or answering possible questions you have you also need to have an idea of what it is you’re looking at. Copying code as mentioned above is a definitive way to ensure that whatever it is you’re working on not going to run. Though ChatGPT can provide a solid foundation or starting point, in most cases that is all it really is and can’t perform the exact specifications you passed to it. This means that cross-reference material with what ChatGPT provides and having an understanding of the possible code or information it generates is important for the proper utilization of the tool. If this is not done, this could lead to catastrophic failure within a project if misused by a student within a senior design project.

6. Hardware Design

From the ground up, a majority of the hardware design has revolved around moving ‘blocks’ - the various subsystems - into the position best suited for making use of as much space as possible. Some of these subsystems are fairly locked into place, like the startup switch and trigger button, where other subsystems can be adjusted around what remains, such as the AI development board or the microcontroller. Certain subsystems also have to be kept together, like the two optical subsystems and the fan subsystem, as the former are dependent on the latter in order to function.

6.1. Hardware Subsystems

The list of subsystems can be considered fairly short. There is the Switch subsystem (OFF to STANDBY), the Fan subsystem (STANDBY to ACTIVE), the Infrared subsystem (Speed Analysis), the Visual subsystem (Accuracy Analysis), and the LED and LCD subsystem (Result). Most of them are self-explanatory in a vague sense, but that is insufficient for proper hardware design. We will be going over each of these individual hardware subsystems, one at a time.

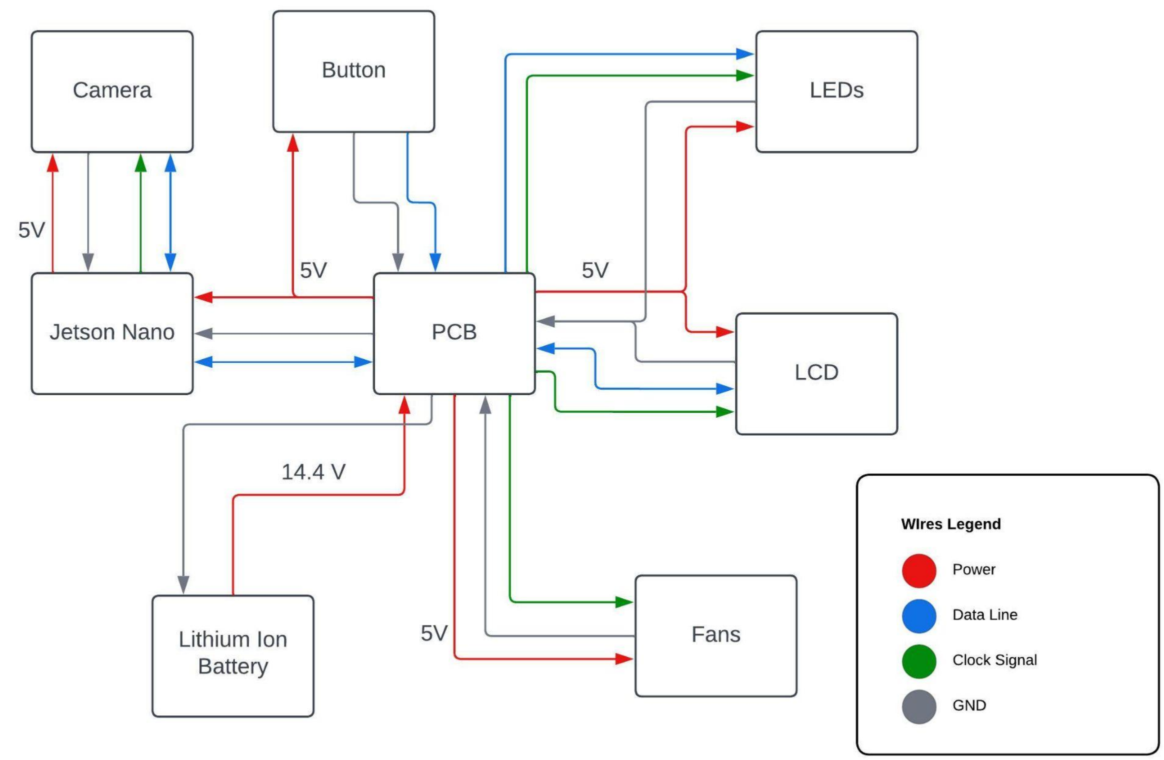


Figure 6.1.1: General Wiring Schematic.

The figure above demonstrates the wiring found within the device. It is important to note, however, that specific subsystems have very limited or overall not sufficiently significant hardware design to include diagrams of the pins involved. This will be written about further down, and all critical circuitry will be shown with diagrams alongside the necessary formulas and mathematical equations where feasible.

Going back to the wiring diagram, we can start at our Power Supply. The Power Supply we're using is a lithium ion battery. This battery will be directly connected into the wiring of the PCB. The Power Supply will provide power to the PCB, and will hold 14.4 Volts. The PCB will have

Four outgoing power wires to send power to the Button, LEDs, LCD, and Fans. These wires will be accompanied by Ground wires. Each Fan will have an additional wire for the Button-activated control of each one. Serial Peripheral Interface (SPI) Communication will be used between the LEDs and LCD, so both systems will include an additional two wires for the Data and Clock Signals. The connection between the PCB and the Jetson Nano will be carried out by two wires using I2C communication, in addition to the two wires to power the Jetson Nano. The Jetson Nano will have one wire connecting it to the camera. This wire will utilize the USB ports found on the camera and Jetson Nano, which will then be used to communicate between them.

6.1.1. Battery Design

Prior to discussing any particular Subsystem, it would be prudent to bring up the nature of the BEESTING's Power Supply. Namely, the fact that the battery we will be using is being repurposed from another device. Since we are repurposing the battery, we have to consider how the connections will work for our device and the subsequent applications.

Ideally, integrating it into the PCB would have allowed for a simpler and easier overall design, but we want to keep the battery separate so that it can be removed from the device and recharged. This will be achieved by adding a slot for the battery to slide and lock into the device. Since this battery was made for a specific device, it also has unique terminals for the connection. This means we need to match the design of the terminals in our device so that the battery has a solid connection and can distribute power properly throughout the device.

The battery has five terminals on it that need to be connected for integration of the battery into our system. The battery that we are utilizing connects to five pins when it's inserted into the port. This then connects to a five pin PCB that runs power from the battery to the PCB in its own device. Three of the pins that connect are used for a clock line, data line, and safety line, to keep track of the remaining power within the battery. Our device will not utilize a battery indicator which means the clock line and data line can be removed from our implementation. With that in mind, we utilize the main positive and negative terminals as well as the battery safety line so that our battery prevents issues from occurring into the system.

6.1.2. Switch Subsystem Design

The first significant Subsystem is one which can be best described as a 'setup' subsystem. The BEESTING device will have both a switch and a button. The button will have no operational effect until the device enters STANDBY mode, which merely requires the switch to be flipped. This switch will connect the power supply to the rest of the device, powering on the Arduino UNO R3 Microcontroller, the NVIDIA Jetson Nano AI Development Kit, and the integrated circuitry. The reasoning for this subsystem is fourfold.

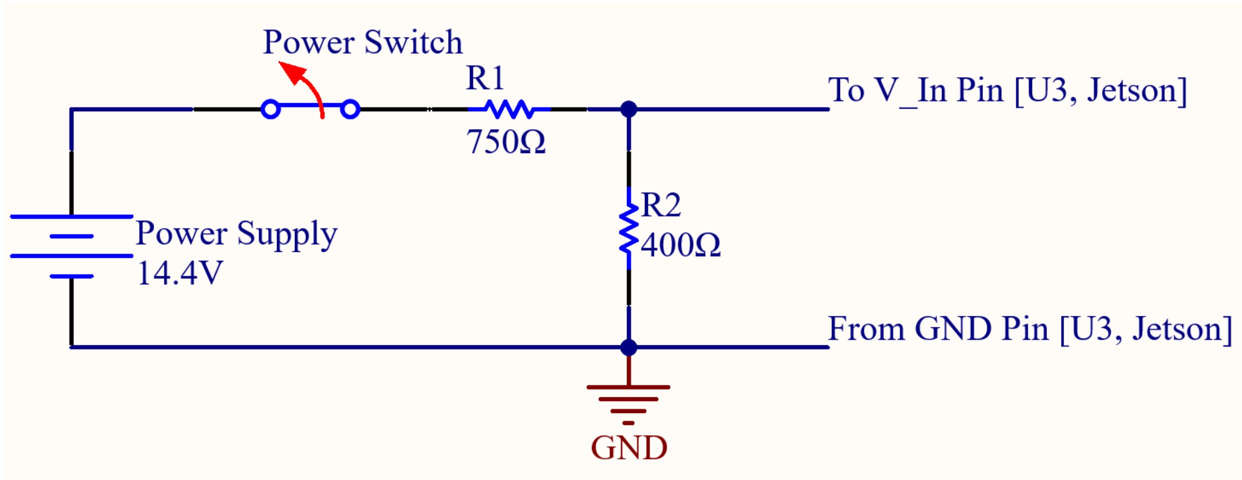


Figure 6.1.2.1: Simple Circuit of the Switch Subsystem.

First and foremost, the existing power supply runs at fourteen Volts - nearly triple the input voltage the Arduino UNO R3 Microcontroller can handle. As such, voltage regulation is a necessity - setting it into the power switch circuit itself simply makes sense for a controlled point of failure. The formula used for the calculation is a fairly simple one, known as the voltage divider equation:

$$R_2 = \frac{V_{Out} * R_1}{V_{In} - V_{Out}}$$

Where R_1 and R_2 are the respective resistors, V_{In} is the 14.4 Volt power supply, and V_{Out} is the intended voltage to run towards the pin - in this case, V_{Out} is five Volts. Similarly, the NVIDIA Jetson Nano - which is also connected to the switch - uses the same amount of voltage as the Arduino UNO R3 Microcontroller, meaning the same circuit can be used to power it, in turn.

The second reason for the use of this Switch subsystem is that it offloads some of the initial operational time for the BEESTING device, allowing for consecutive use to be faster than it would be otherwise. With the Standby being available, it's akin to a passive idling that leaves everything fully warmed up to be used soon after - and repeatedly.

The third reason for the use of the subsystem is closely connected with the second. By leaving the AI Development and Microcontroller boards on and idle, it decreases the wear and tear of repeated ON and OFF activations for the both of them - a common concern for the respective pieces of technology. It's additionally better for the circuitry in general - having it deal with repeat bursts of power when it isn't built with that in mind would only lead to problems.

Finally, this offers safety for the bees; the cartridges for the bees are to be inserted before the button is pressed, and the additional setup steps offers the user of the BEESTING device the chance to confirm that they have been carefully inserted prior to operation. Assuring that the bees are well taken care of is a critical necessity when it comes to device efficiency and accuracy.

6.1.3. LED Subsystem Design

Our device will be equipped with ten Red-Green-Blue (RGB) Light Emitting Diodes (LEDs) placed at the top of the device. Placing the LEDs at the top of the device will give the user a quick and easy way to identify the response of the system. If the LEDs were placed anywhere else on the device, then it would create an inconvenience for the user. The ten LEDs will be split into two rows of five LEDs, and Each LED will represent a respective response given by the bees. Due to there being two different optical Subsystems - the Visual Spectrum Subsystem and the Infrared Spectrum Subsystem - there will be two rows of LEDs. Each row will, of course, correlate to one of the systems.

The schematic design for the RGB LED subsystem is shown in figure 6.1.2.1. This figure helps demonstrate the connections and pins that will be used in the construction of our device. One factor to consider during the design process was to minimize the usage of pins on the Arduino UNO R3 Microcontroller as possible. This has been a considerable challenge due to the need to treat each LED independently from the others. This is because the LEDs are intended to link to individually positioned bees, and in order to represent this the split LEDs are a necessity.

Without any planning, this would lead to each LED requiring three pins each. To solve this, we included Shift Registers, 74HC595, into our design. These Shift Registers are in place to help decrease the amount of pins needed to light all ten LEDs. The Shift Registers will use a daisy chain technique to allow us to use as many LEDs as needed - all without significant drawback to the UNO R3 Microcontroller.

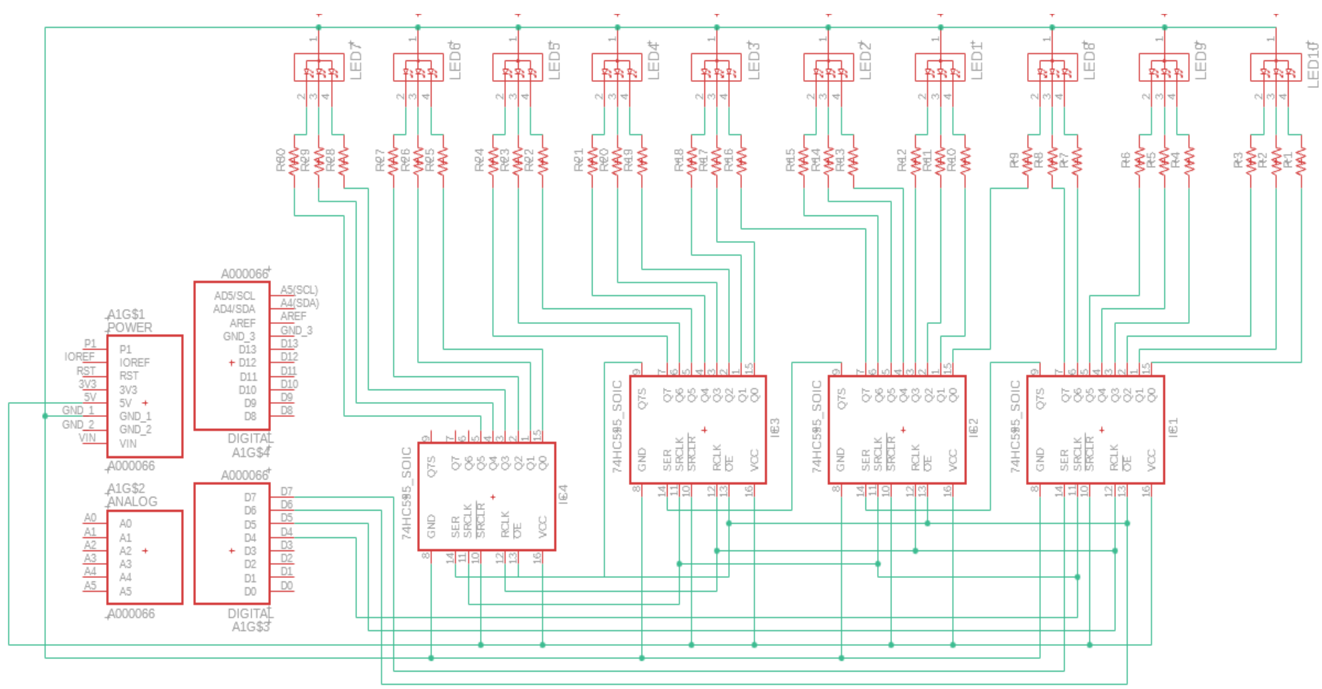


Figure 6.1.3.1: Schematic of the LED Subsystem.

The figure above portrays each component and connections in the RGB LED subsystem. To start, each LED has four pins: a Red, Green, Blue, and Ground pin. The Ground pins will be connected to an Electrical Ground, while the Red, Green, and Blue pins of the LED will connect to a Two Hundred and Twenty Ohm resistor. The resistors are a necessity to limit the current going into each LED, otherwise the high current can overload and burn them out. With the resistors in place, this will protect the LEDs and keep such a thing from happening.

The other end of the resistor will be connected to one of the eight Output pins found on one of the shift registers. Next, one of the Shift Registers will be connected to four Digital pins from the UNO R3 Microcontroller. These four pins of the Shift Register will then be connected to the same pins of each of the other three Shift Registers, which will in turn create a daisy chain. Each shift register will also be connected to ground via pin number Eight.

Finally, each Shift Register will have two pins connected to the Five Volt power source - the same one connecting to the UNO R3 Microcontroller. These pins are pin number Sixteen, which will be used to power the Shift Register, and pin number Ten, the shift register clear pin. By implementing this design, we were able achieve our goal of limiting the amount of pins used on the UNO R3 Microcontroller down to only four.

6.1.4. LCD Subsystem Design

The Liquid Crystal Display (LCD) will be one of the visual aids used to represent the responses and overall detection rate of the device. This is an essential component of our design, because it will notify the user of the bees' responses and additionally offer actively generated statistics for our device. To maximize ease of reading, the LCD will be situated on the top of the device. Putting the LCD anywhere else would be problematic for several reasons, including uncomfortable device orientation for the user and bees alike, alongside needless confusion for the user. The user can easily see the response without anything obstructing their vision.

The two components that are included in the LCD design are the Arduino UNO R3 Microcontroller and the LCD display. The LCD display utilizes five of the Microntroller's pins: three Digital pins, the Five Volt pin and a Ground pin. The Five Volt pin of the UNO R3 will be connected to pin number Two and pin number Nineteen on the LCD. On this LCD, pin number Two is designated to the Power, also known as V_{CC}, and pin number Nineteen is designated to backlight power (BLA). Next, the Ground pin on the UNO R3 will be connected to pin number One, pin number Fifteen, and pin number Twenty on the LCD. Pin number One is the LCD's Ground pin, pin number Fifteen is the PSB pin, and pin number Twenty is the BLA Ground pin on the LCD.

The next part is to connect the LCD to the Serial Peripheral Interface (SPI) pins. The three pins designated for SPI on the UNO R3 Microcontroller are pin number Ten, pin number Eleven, and pin number Thirteen. Pin number Thirteen controls the Serial Clock, pin number Eleven controls the Peripheral Out / Controller In (POCI) pin, and pin number Ten is the Chip Select pin. The

Serial Clock will be connected to pin number Six, the Enable pin, on the LCD. The POCI pin will connect to pin number Five, the Read and Write pin on the LCD. Lastly, the Chip Select pin will be connected to pin number Four of the LCD, which is the Register Select (RS) pin. Below is the schematic for the LCD design of our project. This design was created to decrease the amount of pins used and optimize the overall design of our device.

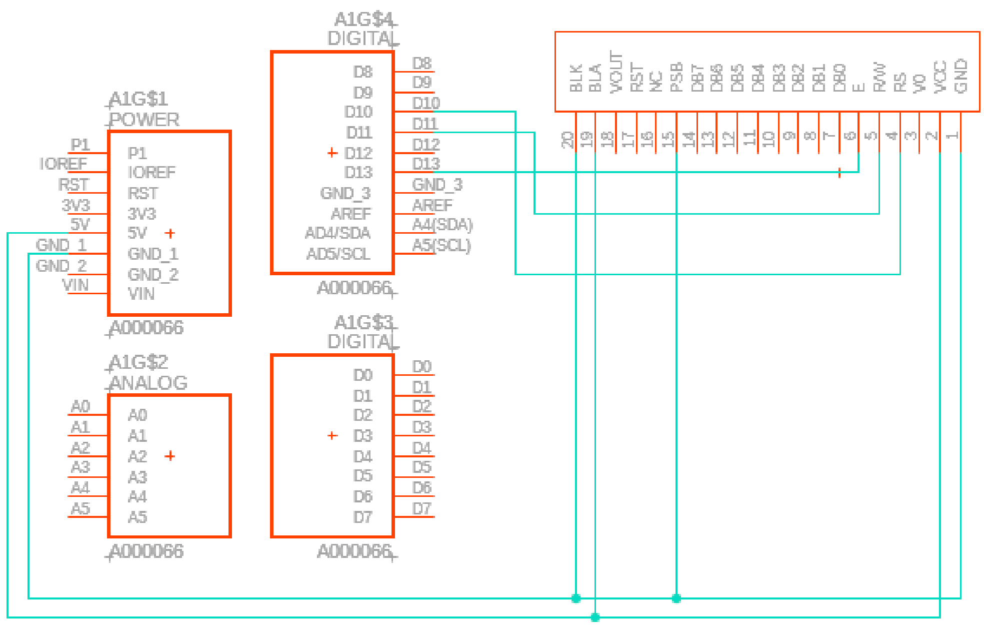


Figure 6.1.4.1: Schematic of the LCD Subsystem.

6.1.5. Fan Subsystem Design

With the Arduino UNO R3 Microcontroller and NVIDIA Jetson Nano powered on together, they in turn interconnect with several other internal components in the background. The Microcontroller operates with the external LEDs, then the LCD and fans. The NVIDIA Jetson Nano, which subsequently assists in turning on the camera, prepares to accept video footage from it for the sake of object detection. All of this happens in under a minute, the various components of the device coming on together and entering STANDBY to work in tandem.

Once we reach STANDBY, the button is accessible for use. This changes the system from being in STANDBY to being ACTIVE, which can be broken down into four different subsystems. The Fan subsystem is the first of the four to operate, simply starting the fans to allow for controlled airflow intake from the front of the BEESTING device. This airflow is subsequently used by both of the optical systems before flowing out through ventilation and an outflow fan.

The button which activates the whole process itself is connected through the UNO R3 Microcontroller, which initiates a clock cycle and activates the various fans within the device.

The fans themselves are connected to the Microcontroller via the Ground pin, a GPIO pin, and the +3V3 pin.

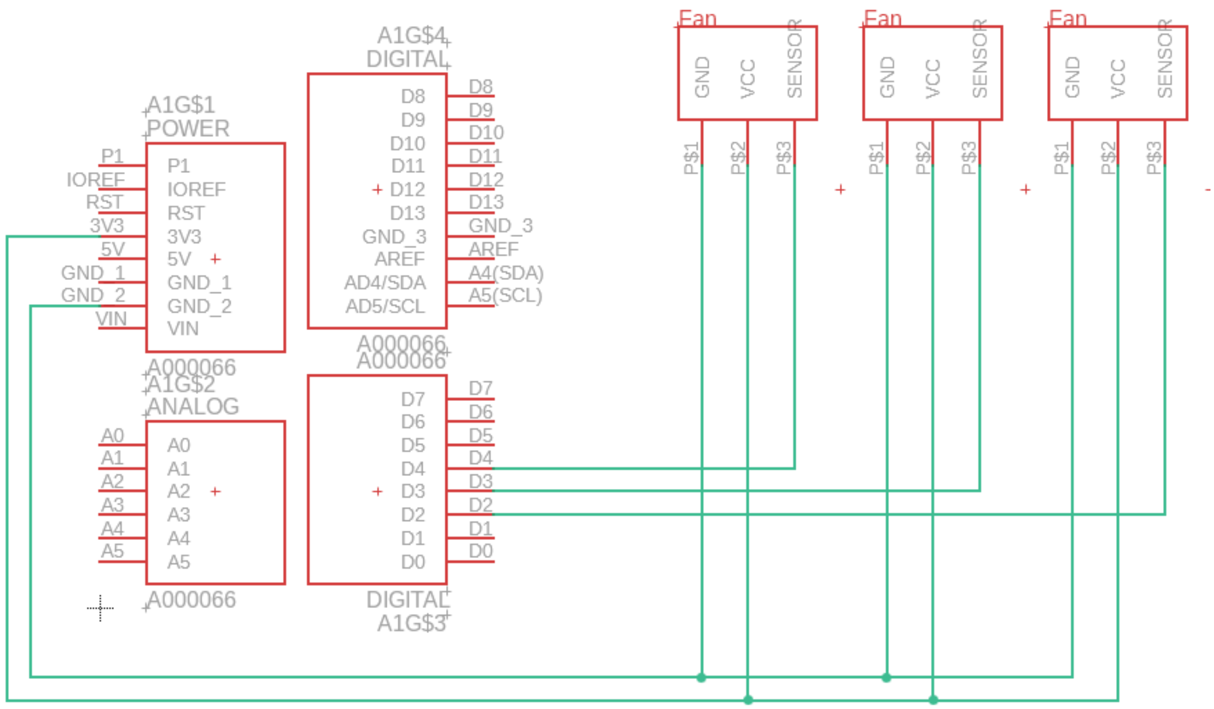


Figure 6.1.5.1: Fan Subsystem Schematic.

As the clock cycle is active, the GPIO pin sends a signal to the fans, unlocking them. With this, they are able to spin freely, and air currents are sent through the device from front to back for several long seconds. Once the clock cycle ends, the GPIO pin repeats the process, which causes the fans to spin down before stopping altogether. Given the signal is being controlled through the Microcontroller, there are only the pin connections to worry about when it comes to the circuit design - no resistors or the like needed.

The speed of the airflow is critical to the device's efficiency, functionality, and design constraints. Without sufficient airflow, the device would struggle to consistently pull in the target sample air without being closer to possible risks - the explosive itself. As such, having the device use fans that are as fast as possible and produce as high an airflow throughput as possible would seem to be the best at first glance. However, considering the necessity of keeping the bees within the device as calm and healthy as possible, high airflow and high noise would both risk the bees becoming agitated, which in turn is bad for the bees' health and detection capabilities.

6.1.6. Visual Spectrum Subsystem Design

In tandem with the fans, the Visual Spectrum Subsystem runs from the same initial trigger - the button being pressed and interfacing with the Arduino UNO R3 Microcontroller. However, the connections for the Visual Spectrum are a little more extensive than the fans are, making use of three pins on one end and two pins on the other.

From the UNO R3 Microcontroller, pin number Eighteen and pin number Nineteen are used together as the Inter-Integrated Circuit (I2C) pair for the embedded system. I2C is a communication protocol that allows for multiple devices to be interlinked and 'slaved' to a master Microcontroller - in this case, the R3. I2C sends binary messages from one device to the other using only two pins, one acting as the Serial Clock (SCL) and the other acting as the Serial Data (SDA). In this case, pin number Eighteen is the I2C SDA, and pin number Nineteen is the I2C SCL.

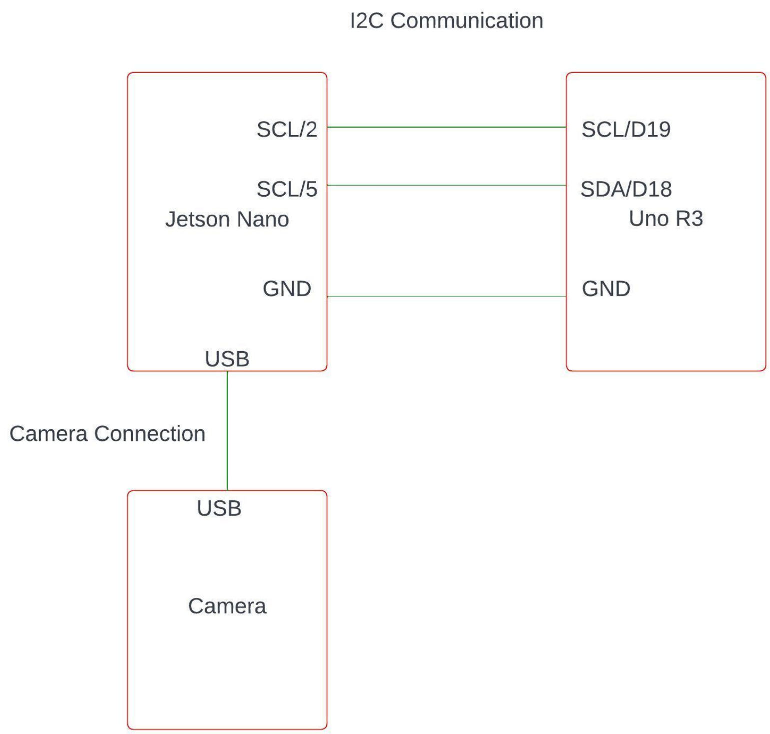


Figure 6.1.6.1: NVIDIA Jetson Nano connection Schematic. Note that the actual board for the Jetson Nano is unavailable, and this is merely a visualization.

These two pins then connect onto the NVIDIA Jetson Nano's board, using pin number Three for the I2C SDA and pin number Five for the I2C SCL. As an additional note, the Jetson Nano uses pin number Two as its Five Volt pin - the one connected to the Switch in Section 6.1.2 - which powers the device and allows it to do what it needs to do. Of course, there is also the camera, but that does not make use of any of the pins on the Jetson Nano. Instead, it uses the USB Port attached to the AI Development Kit, forgoing any need for pin connections.

6.1.7. Infrared Spectrum Subsystem Design

At the same time as the Visual Spectrum Optical Design, the Infrared Spectrum Optical Design will be watching for reactions from the bees. By making use of infrared photodiodes and photodetectors, a second sample of bees will be observed for reactions from their proboscises. In the case that the particulates in the airflow cause them to extend, an electrical signal will subsequently spike from the respective detector, marking the reaction from the specific bee moments later. If the detectors do not spike, that would mean the infrared radiation has not reached them - in other words, the bees did not react. However, this simple explanation for the Infrared Spectrum Subsystem is significantly lacking when it comes to details.

The Photodiodes will not operate with a connection to the Power Supply. Instead, one end for all of the photodiodes will connect into a Ground pin, and the other end will connect to a common circuit known as a Transimpedance Amplifier. This circuit will be subsequently modified for our express purposes. The logic for these changes require some explanation.

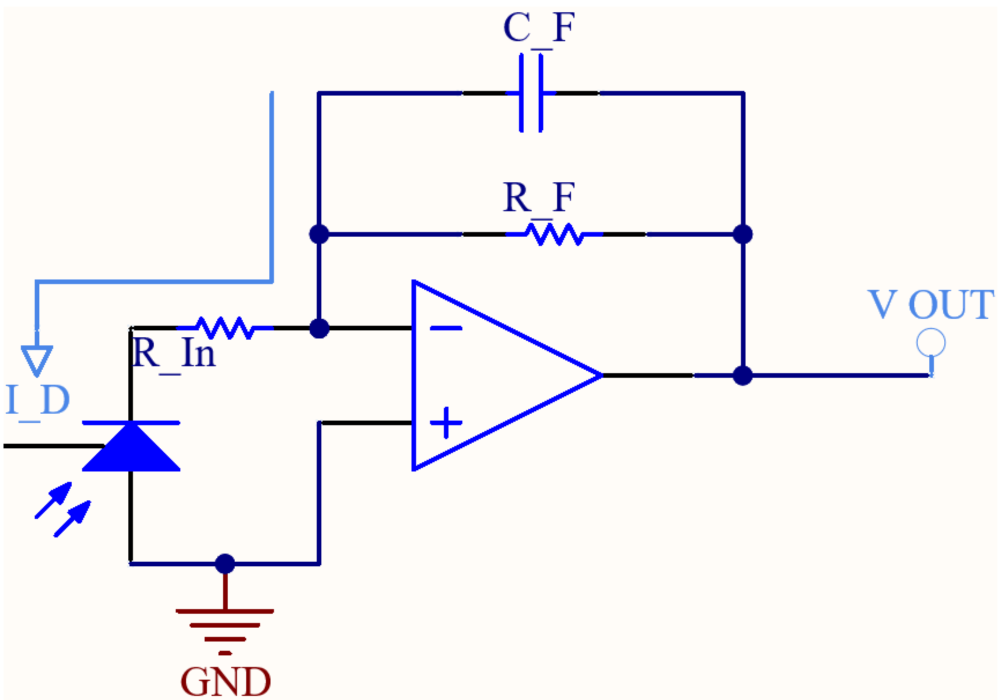


Figure 6.1.7.1: Photodiode Circuit Diagram. I_D is the Dark Current, R_{In} is the Input Resistance, R_F is the Feedback Resistance, and C_F is the Feedback Capacitance.

The Transimpedance Amplifier is a Current to Voltage converter that is specifically used in certain cases, which specifically includes low-power photodiodes. In the most basic form, a Transimpedance Amplifier uses just a single extremely high-power Resistor in the millions of Ohms in parallel with the Negative Operational Amplifier terminal. However, there are also two other points of concern for our particular usage.

First, there’s the concern of burnout for the Photodiode - this is why there’s an Input Resistor as a means to help protect the Photodiode just in case anything happens. The Input Resistor also can be a part of the Gain calculation for the Operation Amplifier - this is to our benefit, as a high Gain is exactly what we want.

Second, there's a major concern for noise coming from the Feedback Resistor - this is called Johnson-Nyquist Noise or Thermal Noise, and it happens when there's sufficient thermal agitation within a resistor. Increasing the Gain of the Operation Amplifier also increases the Johnson-Nyquist Noise in turn. Another concern is Parasitic Capacitance, something that can cause feedback loops and high-frequency oscillations. An easy way to help mitigate Johnson-Nyquist Noise and Parasitic Capacitance is by putting the Feedback Resistor in parallel with a capacitor [65]. This is similar to using an Input Capacitor, which acts as a low-pass filter in a Transimpedance Amplifier.

In this particular instance, however, we should not make use of an Input Capacitor for a low-pass filter. There are several reasons for this. First and foremost, we do not know yet how powerful the signal itself will be - this can be affected by the currently selected diodes themselves, or if a change in Photodiode is needed, by any further tweaks brought by the different sensitivity. Second, the method being used to read the signal is one that focuses on the strength of the voltage sent - low-frequency noise is going to be lower in power, and by extension lower in voltage than that of the spike from the Photodiodes getting the necessary readings. This makes it easier to ignore it so long as other forms of noise are kept low; the Feedback Capacitor is key for that.

The exact values of the Capacitor and Resistors would have to be tweaked once testing begins with the Photodiodes in earnest, as well. However, it can be said beyond reasonable doubt that the Input Resistance (R_{In}) will be small, the Feedback Capacitance (C_F) will be small, and the Feedback Resistance (R_F) will be massive.

The Voltage Output (V_{Out}) will be fed into an Analog Multiplexer, taking in the five inputs and interfacing with a total of six pins. Namely, the Five Volt pin, the Ground pin, the A0 pin, pin number Two, pin number Three, and pin number Four. The Five Volt pin does not connect with the Photodiodes through the Multiplexer, merely connecting to the Multiplexer itself. The Ground pin, however, connects to the Photodiodes through the Multiplexer. The A0 pin is an Analog Control pin. The number Two, Three, and Four pins are all data carriers for the Multiplexer and Photodiodes.

The reason the Multiplexer is necessary for the design is the need for Analog pins. Without the Multiplexer, every Photodiode would require at least one or the Analog pins, which are necessary for other parts of the system. By using a Multiplexer, however, this problem is neatly handled; one Analog pin becomes multiple. Multiplexers only are made in multiples of two; as such, this Multiplexer turns one Analog pin into eight, as four is not enough. We need five pins for the five Photodiodes, after all.

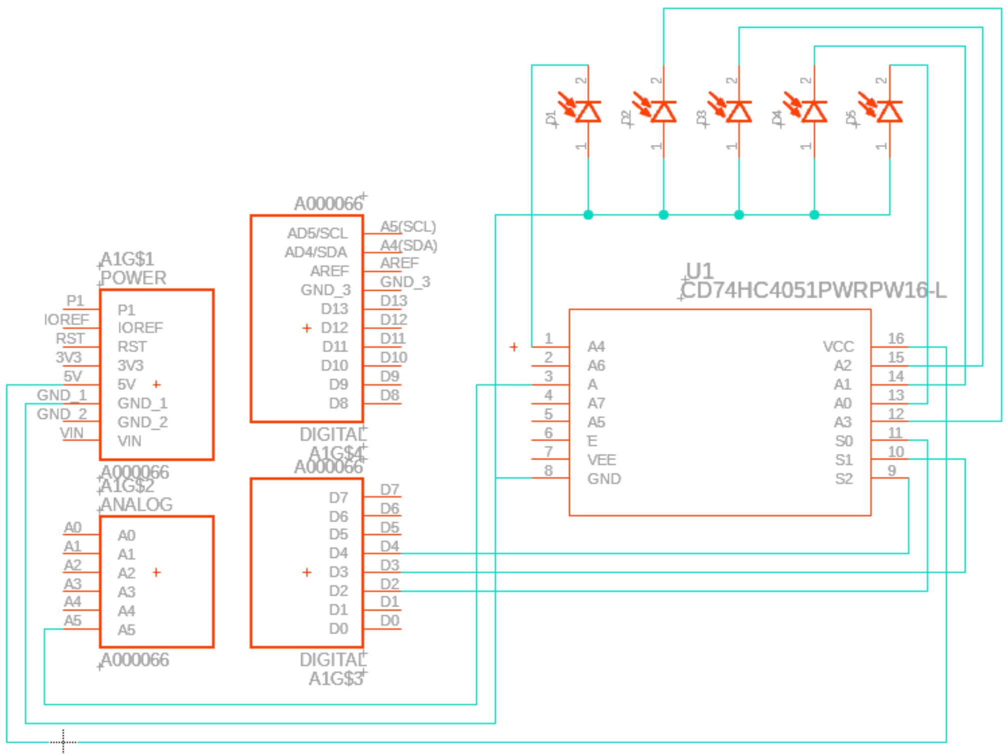


Figure 6.1.7.2: Infrared Subsystem Schematic for the Multiplexer connections. Note that the Photodiodes in the image will have the circuit design in Figure 6.1.6.1; this is solely for ease of visual comprehension.

This system, while it can be considered unreliable versus the visual spectrum optical subsystem, is drastically faster at detection and result confirmation. Instead of operating with curated machine learning algorithms or using image detection with cameras, this is instead a much simpler approach. With this system, we will have the ability to roughly check in advance if there is any risk; if the bees in the infrared spectrum optical subsystem detect anything, it will give the operator time to step away from the target sample and let the other subsystem run its course.

6.1.8. Result Collection Subsystem Design

Given we are working with two different Optical Subsystems, each with their own data and collection process, it's important to keep note of how that data is converted into an output that's easily comprehended and used by a human user. This will be harkening back to Section 6.1.3, and to Section 6.1.4, which discuss the respective schematics for the LEDs and LCD, as well as referring to pin usage in Section 6.1.6 and Section 6.1.7.

The Visual Spectrum Subsystem will be using pin number Eighteen and pin number Nineteen on the Arduino UNO R3 Microcontroller to send data back from the NVIDIA Jetson Nano AI Development Kit. These two pins are the I2C SDA and the I2C SCL respectively, and they have been the sole 'line of communication' between the Microcontroller and the AI Development Kit.

This data is then taken and run through the code written within the Microcontroller. When this finishes, the resulting data is sent through the four Digital pins connected to the Shift Registers, which will send the desired electrical signals to the respective LEDs and help determine the color which they will light up as. The data will also be sent to the LCD after some additional calculations to determine the percentage of bees that ‘agree’ with each other from the Visual Spectrum Subsystem itself. The LCD, given its commands, builds the visual interface and shows the user the results.

Then there is the Infrared Spectrum Subsystem. Using the Five Volt pin, the Ground pin, and A0 pin, alongside pin number Two, pin number Three, and pin number Four, the data from the five Photodiode Circuits is received by the UNO R3 Microcontroller and handled similarly to the Visual Spectrum Subsystem’s data. Afterwards, it’s subsequently sent through a different set of Shift Registers for the LEDs, but sent through the same lines to the LCD.

However, the data from both the Visual Spectrum and the Infrared Spectrum Subsystems is additionally sent elsewhere on the Microcontroller; the on-board MicroSD Card will also be sent a copy of the data for the sake of record keeping within the device. The data the card will contain will be individual logs for each use of the device, with the intent of coalescing the data in order to create detailed spreadsheets for future records and statistical observations.

6.2. Full Hardware Schematic

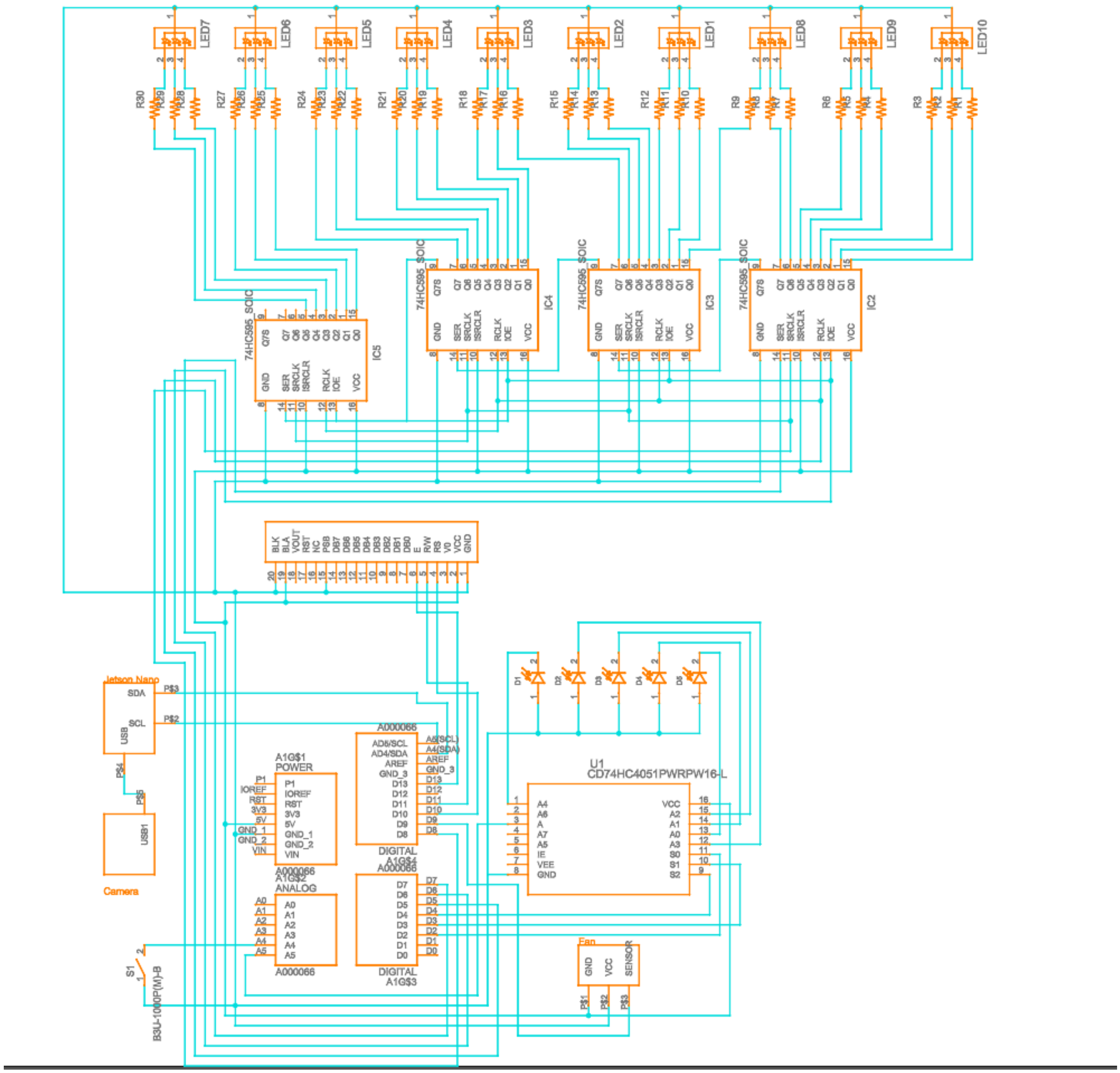


Figure 6.2.1: Full Hardware Schematic.

6.3. Shell Design

When it comes to the housing of the system, the majority of our non-electronic portion of the design will be constructed via 3D printing, specifically using a MakerBot Methode X 3D printer. Versus the various other available options, the Methode X is our best choice between its dual-filament capabilities and existing quality, as well as being relatively available versus other options.

As we are working with a dual-filament printer, this allows for certain creative design options. Making use of both the Overturn ABS filament and the Makerbot SCP 30 support structure, seamless transitions from one to another is not only possible, but optimal. The cheaper Makerbot filament offers the ability to seal the internal support structures for the 3D printed design with significantly fewer internal branching support structures. Branching support structures tend to reduce print quality and durability, leaving the final result with a tendency to be lacking in several respects. By using the support structure in tandem, it can be melted away in a sonicator solution bath, leaving behind nothing but the Overturn ABS Filament - and by extension, the higher-quality print.

To further increase our print quality and our ability to fine tune or save prints that are slightly off, we can also increase the shell size of the prints themselves. Shell size is the amount and thickness of the layers of the print itself, between the outside layer and the inner support structures. The shell size has no gaps in it, acting as a complete, well, shell instead of having the space for air pockets or support structure. In this case, we would be using triple the standard shell size of two layers, going up to a staggering six layers. This is undeniably more expensive, but in exchange it offers a significant increase in strength, durability, and offers an additional degree of waterproofing. On top of that, it allows for sanding to be accomplished faster - more material between the inside and outside means that a rougher grain can be used before the smoother, offering a better and quicker smooth finish.

Of course, we aren't solely using 3D printing. When it comes to the highly sensitive visual spectrum optical system, we will instead make use of CNC Milling. Given our limited options, but similarly small scale, we're likely to make use of a desktop-scale CNC mill by the name of Carvera. This small mill is also connected to a computer, given the information of what the intended cut is, and works through the block of metal much the same way any other CNC mill would. For our purposes, it will be milling the two halves of the Lens Housing Unit.

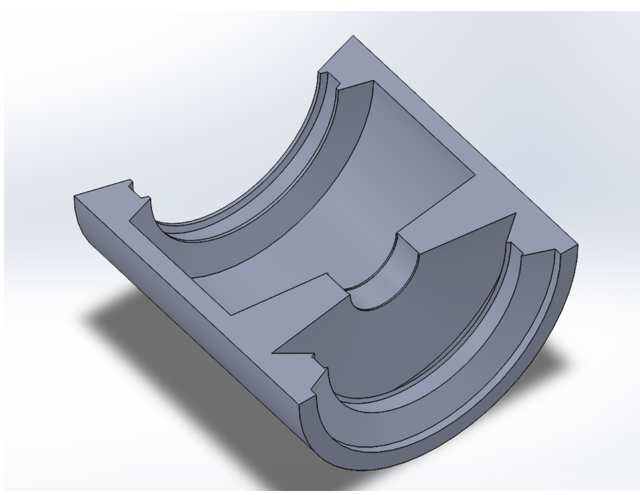


Figure 6.3.1: Visualization of half of the Lens Housing Unit.

The specific reasoning behind using CNC Milling in favor of 3D Printing for the Lens Housing Unit is twofold. First and foremost, the necessity of high precision and accuracy. Inherently, 3D printing tends to have poor precision - hence the need to always sand down printed models - but acceptable accuracy. In fact, in most scenarios, the MakerBot Methode X in our intended setup would work just fine. Using the smallest layer height and the thinnest nozzle, we can achieve print thicknesses as thin as 0.13 to 0.15 millimeters. However, this doesn't take into account either the infill support structure - which would be too small to correctly hold shape - nor the limitations of the printer's ability to handle such a miniscule scale for so long. The resulting print for most 3D printers on such a small scale is a mess of filament and a disastrously failed product - something that theoretically shouldn't happen but practically always does.

Then there's the second reason, which is porosity. 3D printed components are made of plastic filament, and despite the best that this modern variant of the material may offer, this form of plastic has issues with water seeping in. We can mitigate this to the point where the bees and electronics themselves should remain unaffected by this, but the visual spectrum optical system is another matter entirely. As it's meant to be a sealed, low-to-no humidity lens system, any notable amount of water would fog up the lenses and lead to the entire system becoming nigh entirely useless. Similarly, a warmer internal system versus cooler external air would also lead to the risk of the lens system having vapor seep in.

6.4. Finished Shell Schematic

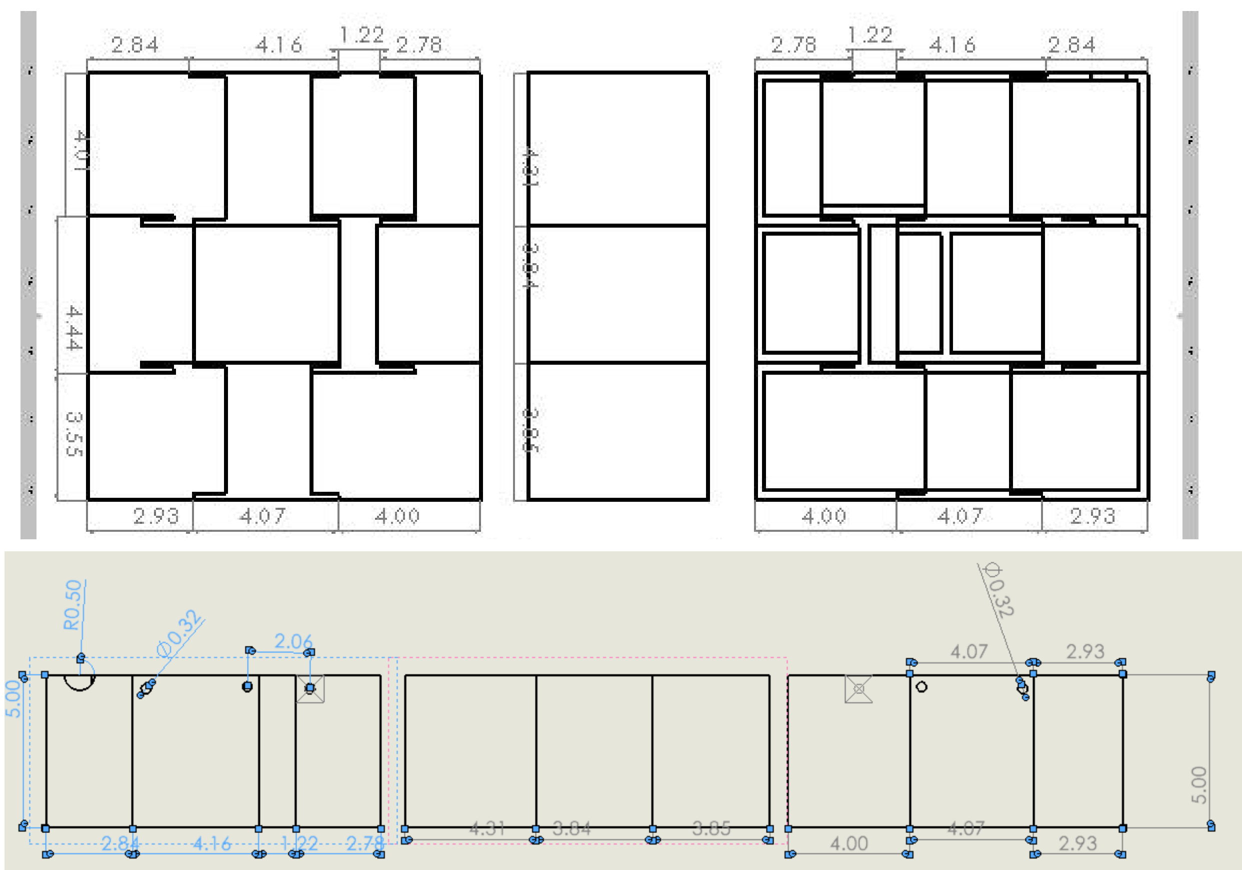


Figure 6.4.1: Shell Schematic of System.

7. Software Design

This project will use a machine learning model for object detection and for embedded software we will be using the C language. The project will have a microcontroller to help control and process all the peripherals. To start with a quick overview of the software, a switch will be used to power the microcontrollers and other peripherals. When the device is turned on it will remain in an idle state until the button, found on the device, is pressed. The button will activate code in the microcontroller, UNO R3 (UNO), to startup the rest of the device. This is where much of the embedded software will start.

The UNO will be programmed to activate the fan system, when the button is pressed. The fan system will control airflow through the system. At this time the UNO will communicate with another microcontroller, an NVIDIA Jetson Nano, to start and transmit data from the cameras and sensors found in each chamber of the device. When the cameras and sensor are done monitoring the bees and data is sent back to the microcontrollers. The data will be displayed on LEDs and an LCD screen for the user. Many of the events that occur with the UNO will be monitored and conducted in C language using interrupts and flags. For this project, the UNO will use serial peripheral interface (SPI) to communicate with certain peripherals like the lcd display. SPI is faster than other common communication methods and works well with multiple peripherals. This will help reduce response time in the system.

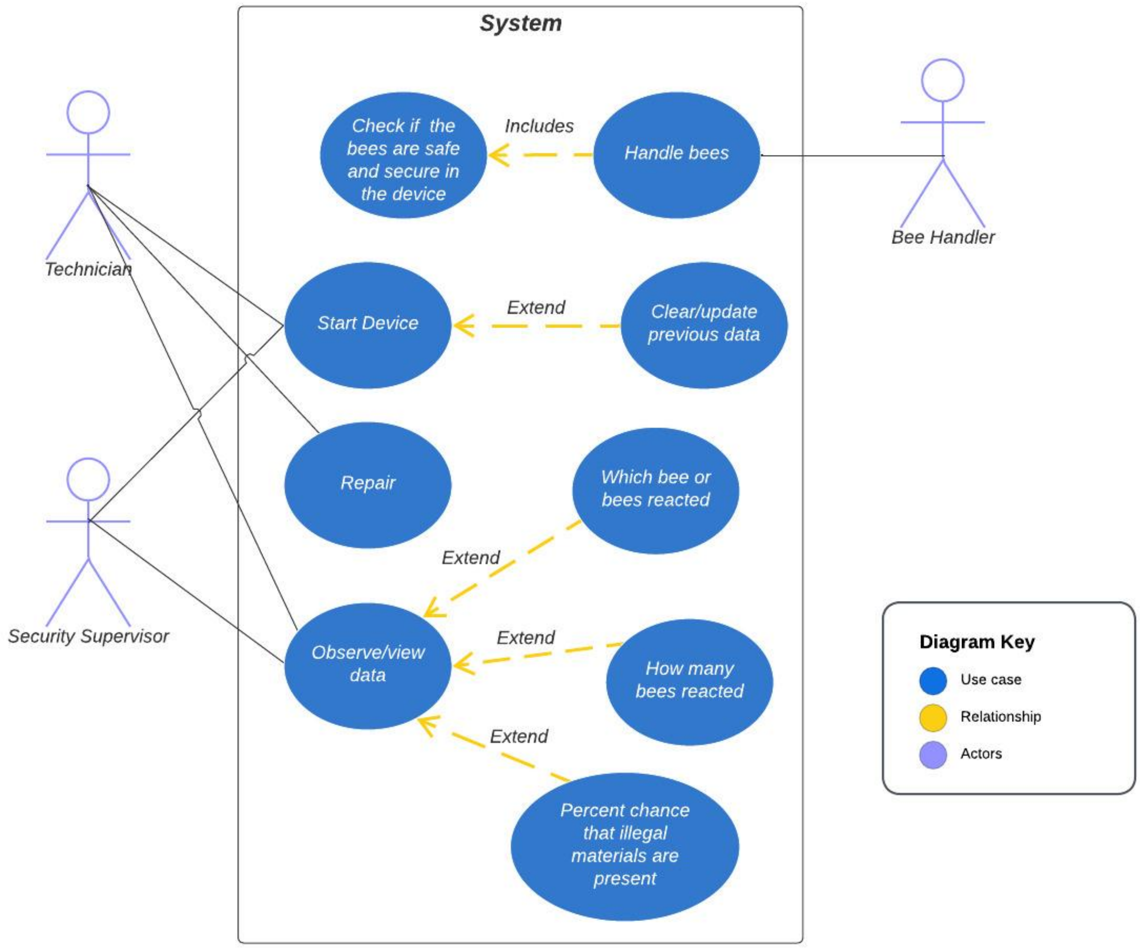


Figure 7.1: Use case diagram. This diagram portrays the relationship between the actors and use cases.

Above is the use case diagram for this project. This use case diagram demonstrates three actors. A bee handler, a technician, and a security supervisor. In this system, the bee handler will only handle the bees. They will make sure the bees are secure and ready to be put into the device safely. The technicians and security supervisor will be handling the device. Both actors can start the device and observe the output, while only the technician will be trained to repair the device if necessary. Customers for this product will be companies that hire technicians and security personnel, thus this is why we included these actors. As discussed earlier a technician and security supervisor/personal can observe the output data. Observing data is an example of a use case found in the system or function of the system. This use case has three extended relationships. These relationships are that the actor can see how many bees reacted to the sample given, which bees reacted to the item in question via which LED has turned on, and the percent chance that there is illegal materials or substances present based on how many of the bees reacted to the sample.

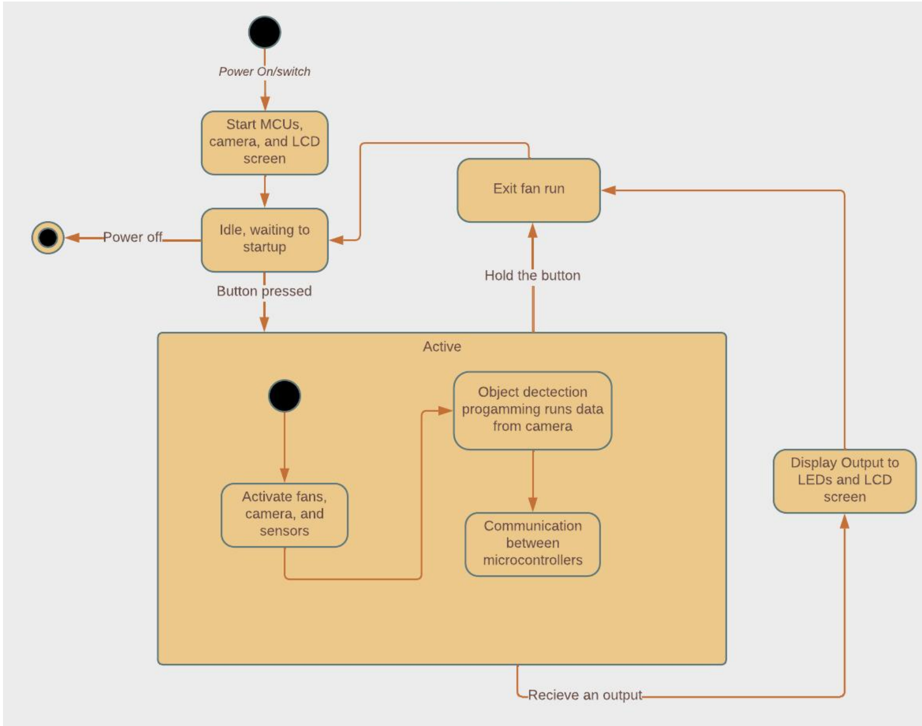


Figure 7.2: State diagram to help describe the behavior of the system

Above is the state diagram for this project. This state diagram helps portray the events of the system at some point during the system's process. The initial state of the device, this is the state before it is powered on, is represented by the solid black dot. When the switch is turned on, the first event to take place in the system, the MCUs,LCD and camera will be powered on. Then the system will remain idle until the next event takes place. The next event to take place is the push of the button found on the device. When pushed, the device will go into an active state. In the active state, the system will activate the peripherals. These peripherals are the fan system, camera, and sensors. The code for each sub-system will be discussed later in this section. Once all the peripherals have finished running their respective processes, the UNO R3 will communicate with the visual output representation to display a response on the device. Once the display is finished, an exit fan will run to cleanse the device of the stimulus. After that the system will remain idle until powered down or the button is pressed again.

7.1. Communication

The design for software communication in this project will be carried out by SPI, I2C, and USB protocols. One of our engineering requirements is to have a response time of less than one minute. To help ensure that the device has quick data transfer, we will predominantly use SPI communication between our peripherals. We found SPI to be the fastest protocol in our research. SPI will be used by the UNO R3 to communicate with the IR sensors, LEDs, and the LCD screen. The UNO R3 will be the master in these situations with the periheals mentioned above as the slaves. The master is in charge of generating the clock signal and syncing the clock signal to all slaves via the SCK wire. I2C will be used to communicate with the NVIDIA Jetson Nano.

When designing our system we plan to use a I2C communication protocol between both the NVIDIA Jetson Nano development board and our UNO microcontroller. The reason for this type of connection is to still allow the AI development board to be in control of the clock signal for the camera system that will be connected through USB to its board. SPI only allows for one master and each peripheral will have to sync to the clock signal that is generated by the master. I2C supports multiple masters and we can use the faster clock signal from the NVIDIA Jetson Nano.

The camera system will need the faster clock signal from the NVIDIA Jetson Nano to transmit and capture real-time data. We want communication from the two boards so that the NVIDIA Jetson Nano can pass the needed data from results to the board so that it can then be put into user output to our LCD display. In the connection the NVIDIA Jetson Nano will function as a I2C master within the system but still maintain operational control over its peripheral system that is the camera. The data will be passed between the two systems so that the results determined inside the Nano Jetson can be relayed back to the UNO microcontroller.

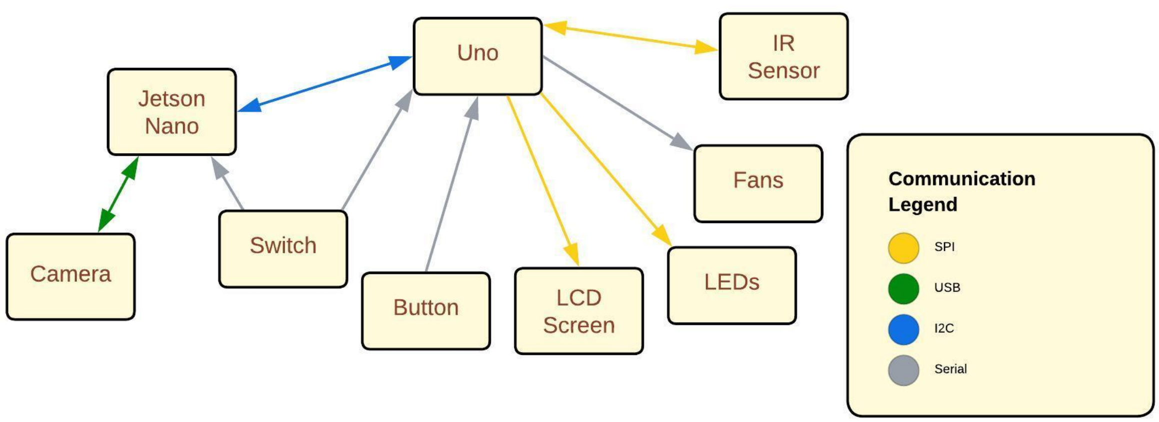


Figure 7.1.1: Communication Block Diagram

More simple communication will occur with the button and switch. The button will be connected to one of the analog in pins on the UNO R3. This pin will either be set to zero or one based on the button. Coupled with a pull down resistor the pin will read zero when the button is pressed. This will alert the UNO R3 to start the system and enter the active state. The switch works in the same fashion.

The switch will be connected to an Analog Input pin on the UNO R3 and function in a similar way as the button. If the switch is flipped on then the pin will read zero. If the switch is flipped to the off position, then the UNO R3 will read one. When the switch is turned on and the UNO R3 reads zero on the pin connected to the switch, then the device will power on.

7.2. Fan System

The fan system will be monitored by the Arduino UNO R3. The fan system consists of multiple fans to control airflow from the nozzle to an exit vent located at the back of the device. To control this airflow several aspects will need to be considered. For example, when the button is first pressed all the fans should start except for the exit fan. This is essential so that the air remains in the device for the bees to smell. If the exit fan is on at the beginning of the process then it will navigate the air we want tested out of the device.

Another aspect to consider is after the data has been taken. After we are done monitoring the bees and have output our data we want to get rid of the stimulated air that resides in the device. The device must be cleansed before it can conduct another test. To do this we will turn off all fans except for the exit fan. The code will tell all other fans except the exit fan to turn off, while turning on the exit fan.

With all this in mind, the code for the fans system will activate when the button is pressed. The event of the button press will be monitored by an if statement. If the button is pressed it will run the code to start each fan except for the exit fan. After a minute has passed of the fans running, then all fans will turn off and the exit fan will turn on. After twenty seconds has passed the exit fan will turn off and the device will remain idle until powered off. Figure 7.2.1 is a supplementary flowchart that demonstrates the programming steps for the fan system.

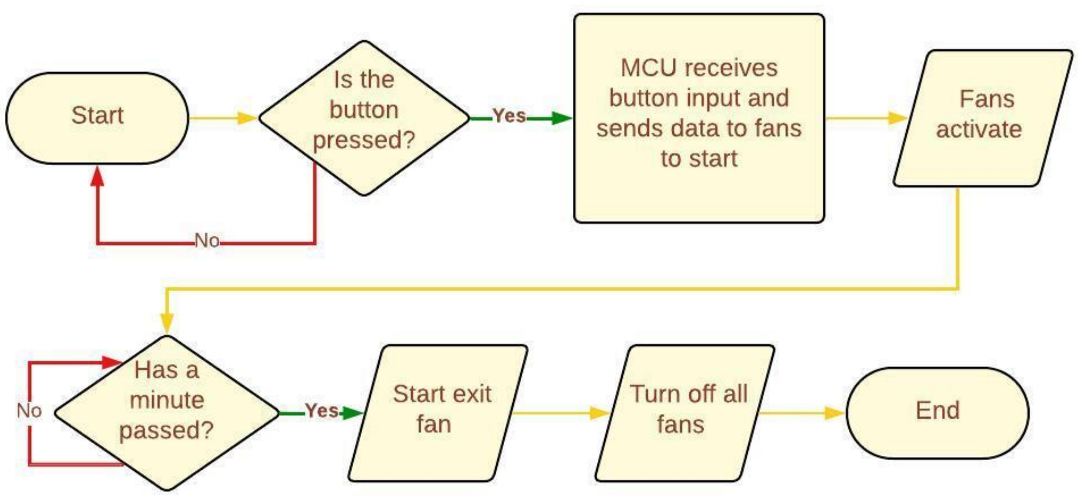


Figure 7.2.1: Fan Subsystem Flowchart.

7.3. Visual Output

The output of the system will be displayed on both LEDs and an LCD display. Below will discuss the design for both visual representations. The purpose of the visual representation is to give the user a visual confirmation of what the response is. Without these visual aids the user would have to observe the bees themselves, which defeats the purpose of our device. We included two visual representations to increase accessibility of our device. We came to this conclusion because we realized there may be users that are visually impaired or are color blind. Using two different visual aids will help to alleviate these concerns. This will also increase the amount of individuals that can use our device.

7.3.1. LED Software

The first visual representation we will cover is the LEDs. The LEDs are pretty simple. We must light up the LEDs in correspondence to the observed results. This is done with programming from the Arduino UNO R3. The UNO R3 will be programmed to tell the LED to light up and what color to present to the user. Each LED is independent of one another, this creates the problem of using too many of the microcontroller GPIO pins. To help solve this we will be using shift registers. The UNO R3 will communicate with the shift registers to control the LEDs. In the case of a successful result, the bee proboscis is shown, the LED will light up green. For an unsuccessful result, the bee shows no response, the LED will light up red. These events will occur by connecting the LEDs to the UNO R3. By directing a pin to the output of the LED, we can tell the LED to turn on and specify what color to be. We will further specify what color to light the LED using if statements. For example, if the response is successful then run the code to light the green LED. If the response is unsuccessful, run the code to light the red LED. The flow chart below further demonstrates this LED design.

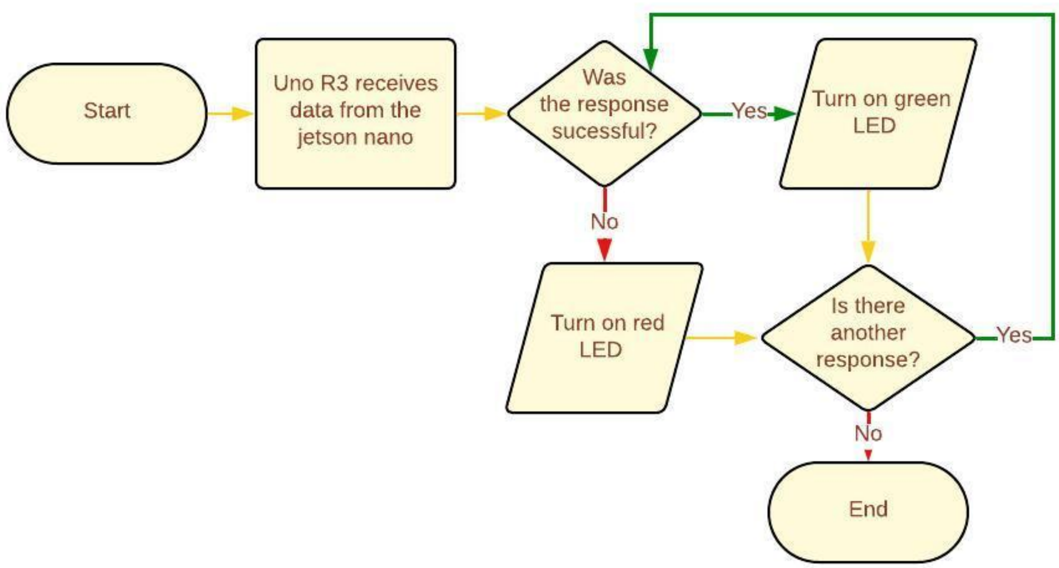


Figure 7.3.1.1: LED Flowchart.

7.3.2. LCD Software

The LCD screen will be another form of visual aid to represent the response of the system. The screen will be placed towards the top of the device. Our device like many others will have an idle state and an active state. The screen will be designed to have a display differently for each state. The idle state will occur when the device is turned on and the active state is after the user has pressed the button.

During the idle state, when the device is first powered on, the screen will prompt the user with instructions. Instead of having a blank screen with nothing outputted, the screen will inform the user that the device has turned on and to press the button to start the system process. This was included to guide users through the process of using the device. This additional aid will help lower the time it would take to inform an individual on how to operate the device. Once the button has been pressed the screen will change to the response/output screen that is portrayed during the active state.

For the active state the LCD screen will display which bees showed a response, sticking out their proboscis, to the stimulus provided, the overall percentage of bees that showed a response and the response time of the system. These statistics will be displayed with help from the UNO R3. The UNO R3 will be programmed to send data to the LCD screen. To display which bees showed a response the screen will portray a grid with two rows and five columns. Each row will represent the IR sensor or the camera, while the column will represent the bees. The grid will specify which bee responded by showing either a check or cross. The check means that the bee showed its proboscis and a cross means it did not. Below the grid will be additional statistics. The percentage of bees that showed a response in each system will be displayed. At the bottom of the screen is the response time of the system. Including this parameter is an accurate way to help demonstrate one of the engineering requirements we have put on the system. Instead of having to time each instance with an external clock, we can use the system to keep track of the time. This will make sure we satisfy the requirement and help track our progress. Below is a visual of how the user interface will look in the active state.

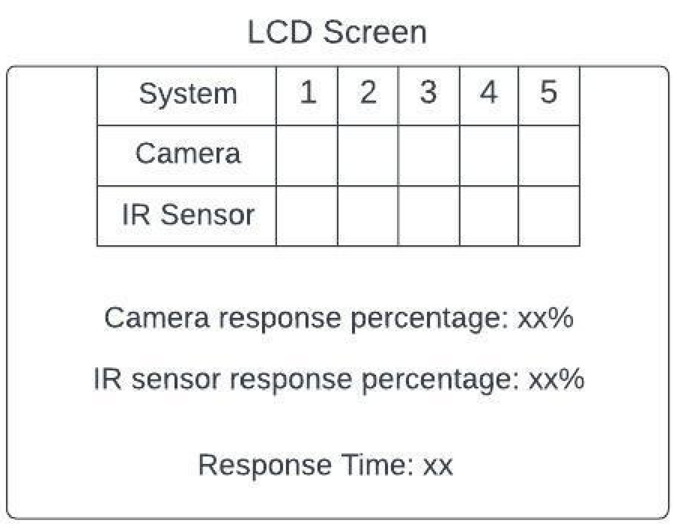


Figure 7.3.2.1: Example Screen of the User Interface.

7.4. IR Sensor Software

Our project will use two systems to observe the bees. In this section we will discuss the IR sensor system. The IR sensors will be in a separate chamber than the camera. While the camera will be connected to the Nvidia Jetson Nano, the IR sensors will connect to the UNO R3.

As discussed in the previous hardware section the IR system will use five IR sensors for each bee. This means that the UNO R3 must take in five analog inputs from each sensor. This creates a problem because of the limited amount of analog pins on the board. The solution is to include a multiplexer to increase the amount of analog pins on the UNO R3. The UNO R3 will be programmed to communicate with a multiplexer to determine if the voltage of the input pins is either high or low. The voltage level will indicate whether the bees responded or not. To read the voltage level a function in the arduino will be used. This function is called digitalRead(). DigitalRead() will indicate and return a value of high or low to the UNO R3. This value is interpreted by the UNO R3 and sent to the LCD and LEDs as a response.

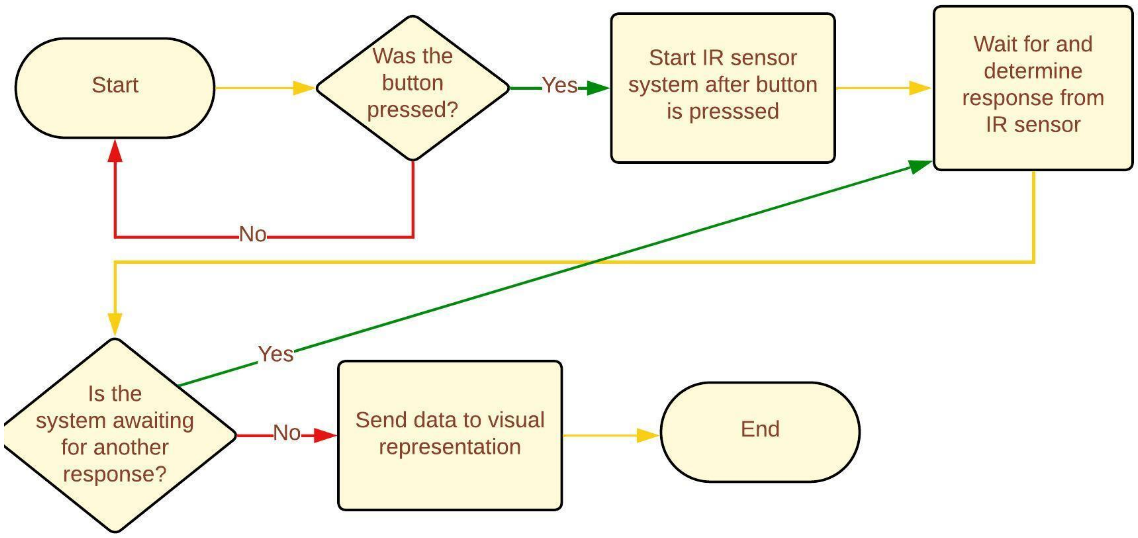


Figure 7.4.1: IR Sensor Flowchart

7.5. Machine Learning Model and Training

For software design, Python will be utilized for the implementation of the YOLOv4 algorithm. The reason we are utilizing a slightly older YOLO version is due to the heavy implementation that it has in many object detection applications as well as the extensive testing the algorithm has gone through. The YOLOv4 algorithm will be trained using images found from both online and during tests of our device, if possible, to ensure that the proboscis of each bee can be detected within the device to provide the necessary feedback we want.

The goal is to train the algorithm with as many images as possible to ensure that it has a high degree of accuracy when the device is in use. Since we will be utilizing the NVIDIA Jetson

Nano, this board development kit comes with different functions and libraries - as mentioned in section 3.6.1. - to allow for training on the board so that we can train our algorithm to detect the object we need. To train the algorithm properly we'll have to manually annotate each image to identify the object class. This will require identifying the object within each image to train the model to the best of its ability.

Since the algorithm will be trained offline, we will be utilizing a form of training known as a "Bag of Freebies" [53]. The idea behind a bag of freebies is to augment images that we will be using to train our model. A more detailed explanation from YOLOv4: Optimal Speed and Accuracy of Object Detection, "The purpose of data augmentation is to increase the variability of the input images, so that the designed object detection model has higher robustness to the images obtained from different environments". Since our model involves a living subject within a confined space, the environment will be relatively stagnant, but due to the small nature of what we are detecting, having a model that can detect the bees' proboscises regardless of possible overlapping due to legs or its head being at a different angle when they stick their proboscises out is something we must consider.

Since the machine learning aspect of the project is important but is not the bulk of this project, the method used within the "bag of freebies" will be relatively simple and will involve using mostly pixel-wise adjustments such as stretching, rotating, or distorting the images. More complex image augmentation might be considered depending on the results from initial testing with the dataset created and the results obtained. This will also be implemented with what is called a "Bag of Specials" which also increases the accuracy of the model. The bag of specials utilizes module plugins and post processing to allow for the higher accuracy of the model.

Once the model has been trained and implemented within the device, it will work in conjunction with the camera to pass the imagery from within the chamber to the model to identify what if the object is detected. Depending on the number of proboscises detected from each of the five bees will then determine a degree of accuracy within the device. For instance, if five are detected, then the information will be passed along to other portions of the device and provide output to indicate the accuracy to the user of the device.This communication will be done between the camera and the NVIDIA Jetson Nano board then passed to the microcontroller within the device. The model will only start analyzing the images once input has been detected from the user and the cameras/sensors record and pass the information to the board so that it can save power and sit in an idle state if possible.

Since we are utilizing a custom dataset, the first step before implementing the object detection model will be to use Roboflow to create and annotate the custom dataset that will be utilized. This will then be implemented into the YOLOv4 model. To ensure that we maximize the FPS through the Nano and that detection is achievable the model will then be run utilizing Pytorch. Pytorch will be the deep-learning framework and it will be what is used to provide training for the model. This will utilize tensors and graphs for the implementation, making it easier to train our model detection. From there the object detection will then be run with the input from the camera so that detection can be made.

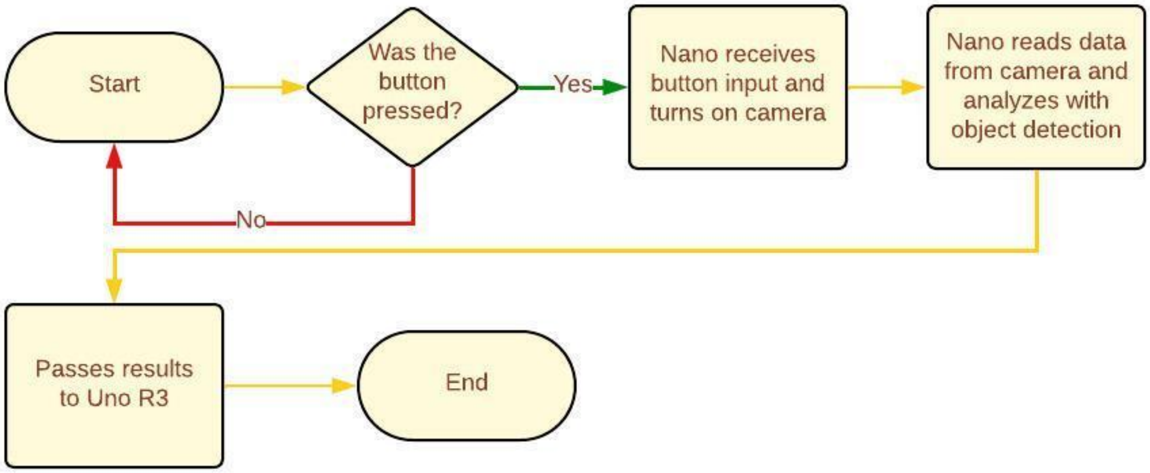


Figure 7.4.1: Machine Learning Flowchart.

In order to ensure that our model is working, the parameters for training it will need to be altered. For instance the batch size would need to be changed to find a proper model. This means changing the number of images per iteration to find a model that isn't under trained or over trained. This requires having multiple datasets to train our model with to optimize accuracy for the best possible return. The dataset will start at one hundred images and from there will be changed with each iteration either by adding more images or removing images to find the best model that works.

In order to find the properly trained model, after each batch size is changed all other parameters will be altered one after the other. First the activation function parameter will be tested for each training model. Changing the activation function for each batch and testing out the functions that are best suited for YOLOv4 will allow for increased performance of the model. To keep with constraints the number of activation functions that will be implemented will be kept to minimum, and because linear functions will be avoided for the most part, this means that functions like ReLU and GeLU will be utilized with any variations that the activation functions have. Utilizing the non-linear activation functions will allow for a more optimized training of the model. This will also change the accuracy of the model in order to find which function produces the best trained result. Ensuring the design of our model with the correct activation function will also eliminate any possible gradient descent that can be seen from linear or sigmoid functions. One problem will be neuron death that may occur with using ReLU for example but is accounted for with other activation functions that will be utilized when training the model.

Another important parameter that will be modified for optimization of the model will be the learning rate. In order to avoid a model that takes too many iterations to train or a model that is unable to detect anything with accuracy at all, a proper learning rate needs to be acquired for a model that can operate within the speeds we want. The number of iterations that the model runs for training will be limited as well. Once again this is to ensure that the accuracy and the training of the model can be optimized. The number of iterations that will be run will start small then will either increase or decrease based on results.

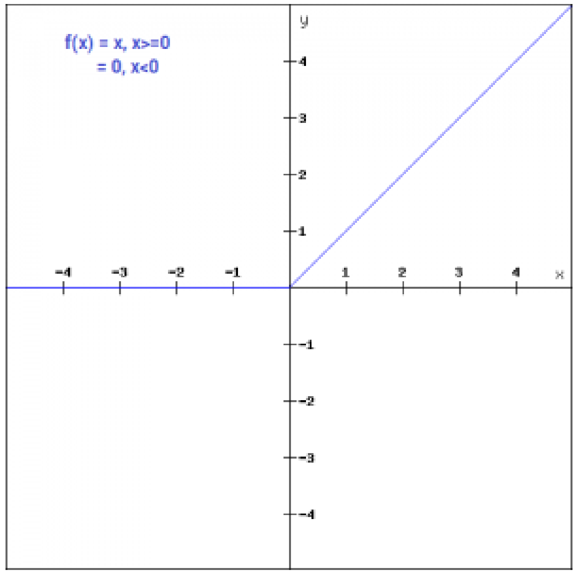


Figure 7.4.2: ReLU activation function, stays within range of 0 to -1.

In order to determine how each parameter affects the outcome of the model, the F1 score will be monitored. The F1 score is determined using a formula called the Precision-Recall Curve. The formula is:

$$\frac{(Precision\ x\ Recall)}{\frac{(Precision + Recall)}{2}}$$

Using the F1 score after each parameter change will allow for determination on which parameters optimize our model, specifically to manage the best form of implementation into our system, while also ensuring the best degree of accuracy. One last process will be the data collection from the camera. The data passed from the camera will be filtered and enhanced so that the model can detect the bees' proboscis.

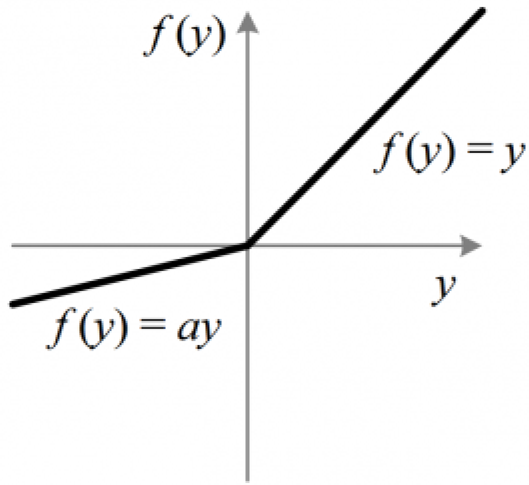


Figure 7.4.3: Parameterised ReLU which accounts for dead neuron problem in ReLU.

7.6. Software Used

This will cover the software that we have selected to help complete this project.

Software	Description
Arduino IDE	Arduino IDE is an integrated development environment (IDE) for embedded systems. Developed by Arduino for the use of embedded systems and processors. Arduino IDE uses a C/C++ compiler and is available with Windows, Linux, and MacOS systems. This is a software familiar with the team after taking embedded systems.
Google Colab	Google Collab will be used for machine learning algorithms and object detection code. The code for object detection will use python and openCV.
Visual Studio Code	Programming IDE used for various coding languages. This software will be used to program some of our machine learning algorithms. This IDE is also used to build HTML and CSS code for our website.
AutoDesk Eagle	AutoDesk Eagle will be used to create PCB designs and schematics for our project.

Software	Description
Ultra Librarian	Ultra Librarian is where we will find the footprints for our PCB design. Ultra Librarian is a free resource to help ease PCB design with its downloadable CAD models.
SnapEDA	Similar to Ultra Librarian, this is where we can obtain footprints for our PCB and schematic designs.
Lucid	Lucid is used to create many of the diagrams present in the report.
Solidworks	3D Modeling software to use for 3D printing.

Table 7.5.1: List of Software Used in the Project.

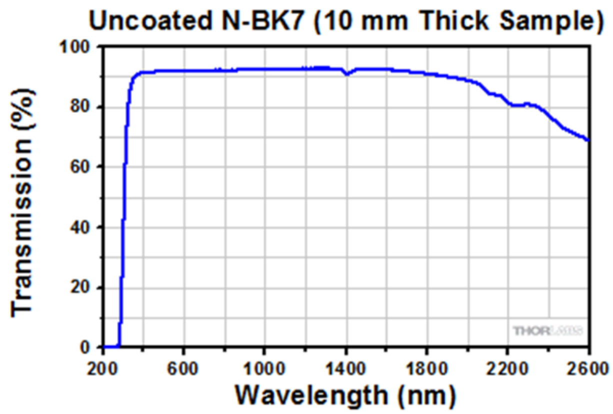
8. Optical Design

The BEESTING device hinges on three critical facets. The first is the bees themselves, which are a necessity for it to even function, and are the sole ‘detectors’ within the device itself. The second is the object recognition machine learning algorithm, which is absolutely needed in order to catch the proboscises of the bees automatically. The third are the two optical systems which make up the ‘observers’ of the bees, acting as the middlemen between the biological and the mechanical.

8.1. Visual Spectrum Design

8.1.1. The Lenses

In the device that we will be building, we will be using a compact three lens imaging system in the visible light spectrum as well as a simple photodetection system in the infrared spectrum to image the bees. This compact design is extremely advantageous for our use cases of a small hand held device that is easy to handle but is still relatively cheap and affordable. The table below shows the information for only the lenses used for the visible light imaging system.



N-BK7 Bi-Convex Spherical Singlets	
Lens Shape	Convex/Convex
Material	N-BK7 (Grade A)[a]
Wavelength Range[b]	350 nm - 2.0 µm (Uncoated)
Design Wavelength	587.6 nm
Index of Refraction	1.515 (@ 633 nm)
Surface Quality	40-20 Scratch-Dig
Surface Irregularity	$\lambda/4$
Spherical Surface Power	$3\lambda/2$
Abbe Number	v_d=64.17
Centration	≤3 arcmin
Clear Aperture	>90% of Diameter
Diameter Tolerance	+0.0 mm / -0.1 mm
Focal Length Tolerance	±1%

Figure 8.1.1.1: Transmission Range and Physical Characteristics of N-BK7.

Item #	Diameter	Focal Length	Dioptera	Radius of Curvature	Center Thickness
Thor labs LB1811	1"	35.0 mm	+28.6	34.9 mm	6.8 mm
Thor labs LD2568	9.0 mm	-9.0 mm	-111.1	-14.4 mm	2.0 mm

Table 8.1.1.1: Table of Visual Spectrum Lenses.

8.1.2. Optical Design Equations

Equations are the backbone of Optical Science, allowing us to track the effects which lenses have on light. Geometric Optics is especially useful when it comes to the formation and subsequent modification of lens systems, as the formulas and calculations focus on determining ray pathways from the Object to the Image.

The foremost of these is the Lensmaker Equation, which relates the physical traits of a lens to its Focal Length. This equation is used in every Optical System. In a converging lens system, this Focal Length is positive, representing where the light in the system comes to a point. In a divergent system, the Focal Length is negative. The formula is:

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

Where f represents the Focal Length of the lens, R_1 and R_2 represent the respective Radii of curvature of the first Surface - in the order of light impacting it - and second Surface of the Lens respectively, and n is the Refractive Index of the Lens.

We can then use this Focal Length via the Image Position Equation. Also known as the Newtonian Position Equation, the formula can be used to locate the Real Image relative to the Position of the Lens itself. This equation is vital to any optical system, as without knowing the location of the Real Image, there is no way to view the Data the System obtains with any degree of clarity. The formula is:

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}$$

Where f is the Focal Length of the Lens, S_1 is the distance from the Real Object to the Lens, and S_2 is the distance from the Lens to the Real Image formed by said lens. The uses for this are extensive, though for our purposes we have only one significant use.

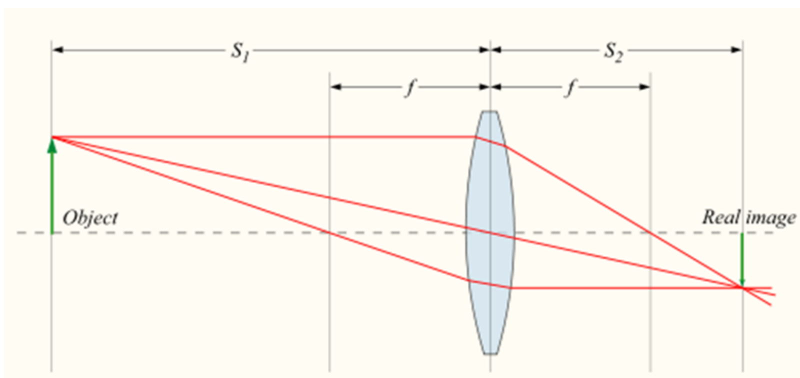


Figure 8.1.2.1: Visualization of the Image Position Equation.

The final equation for our intended Visual Spectrum Optical Design is the Magnification Equation. The Real Image an Optical System produces is rarely the same size as the Real Object being imaged on the other end of the system. This equation makes use of the relationship between the distance between the Real Object to Lens and the distance between the Lens and the Real Image in order to form a ratio for magnification. Better known as the Magnification Factor, this ratio is used to determine the Size Ratio between the Real Image and Object.

In the case of the BEESTING, we intend for the Real Image to be less than a third of the size of the Real Object, changing a 6.6 millimeter radius to a 1.92 millimeter radius. This is due to the necessity of making the Real Image compatible with the intended Optical design. The formula for the Magnification Equation is:

$$M = -\frac{S_2}{S_1} = \frac{f}{f - S_1}$$

Where M represents the Magnification Factor, which can be either positive or negative, *f* is the Focal Length of the Lens, S_1 is the distance from the Real Object to the Lens, and S_2 is the distance from the Lens to the Real Image.

8.1.3. Tackling The Multi-Lens System

Previously, we have only been talking about imaging when it comes to single lens systems, but in practice, very few systems are single lens systems. BEESTING's systems are certainly not single-lens, either. There are a few different ways for us to solve this particular challenge; in this case, we will first start with the object, then carefully calculate how it interacts with the first lens in the system via formula and simulation.

From this, we find where the real image is created. Once the position of the real image is found, we are then free to move on to the second lens and begin the process anew, learning how it then interacts with the first real image and creates the second real image in its place. This process repeated a final time with the third lens to give us our final third real image - the one that is projected onto the camera. This process is fine and reliable, but it takes a fairly significant amount of time. As such, we are making use of a modern tool used to simplify the process: MATLAB.

8.1.4. MATLAB

MATLAB is a programming platform specifically designed for scientists and engineers. This platform has a host of high-complexity toolkits and calculation schema. It can design models, run simulations, read and run test data, complete high-fidelity numerical calculations, process images, and boasts a host of other abilities. One of the primary appeals of MATLAB, however, is its capabilities with matrix and array mathematics.

Many technical issues across a multitude of professions involve matrices or vectors, and most platforms or calculators struggle with handling either once a sufficient complexity is reached. MATLAB, built specifically for these high-complexity mathematics, has no such issues or complications. Additionally, MATLAB also has a large library of built-in functions that reduce the complexity of the user's code, easing work for the user yet further. The library includes pre-made toolboxes that a user can navigate through easily; they can call commands designed for specialty tasks, such as optical design or image processing. The working environment is also designed to streamline the coding process, giving the user facilities that manage workspace variables, export data, and debug code - another point in MATLAB's favor.

Handle Graphics is MATLAB's built-in graphics system. It processes images and animations and creates two and three dimensional visuals. Commands can also be used to build a GUI and completely customize the appearance of graphics. This can be used in conjunction with other programming languages, as MATLAB supports integrating with C, Python, Java, and more languages.

For this project, MATLAB was used for ray tracing and determining the best optics for our system. The programming style made it easy to input distances between lenses, glass types, and other key information and compare it. This became essential when calculating the optical system because going in to the design of the system, there are only four critical design constraints: the height of the object, which is 6.6 millimeters, the height of the real image, which is intended to be 1.92 millimeters, the total size of the lens system from object to camera, which should be at most one hundred and fifty millimeters - this is to ensure that our system will still be portable - and lastly and above all, keeping it relatively cheap.

With thousands of lenses available to choose from, from Thorlabs, Edmund optics, and Newport, the process became a complicated mess. We did, however, figure it out. What's important to note, however, is that even cheap lenses are fairly expensive; just for the three lenses operating for the visual spectrum, the cost without any kind of shipping exceeds forty dollars.

8.1.5. Final Visible Optical Design

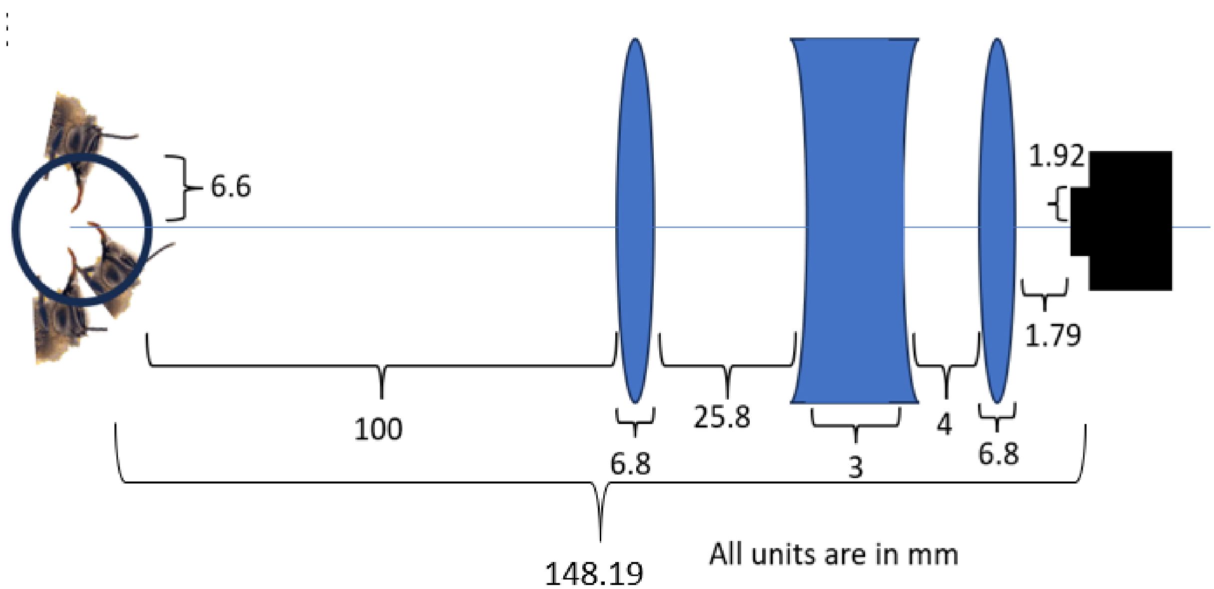


Figure 8.1.5.1: Finished Visible-Spectra Optical Design.

8.2. Infrared Spectrum Design

The second optical design, the Infrared Spectrum Design, is notably less complicated versus the Visual Spectrum Design. Instead of operating with a lens system or a camera, the optical design will be making use of photodetectors - also known as photosensors - in concert with careful reading of the electric signals they will send.

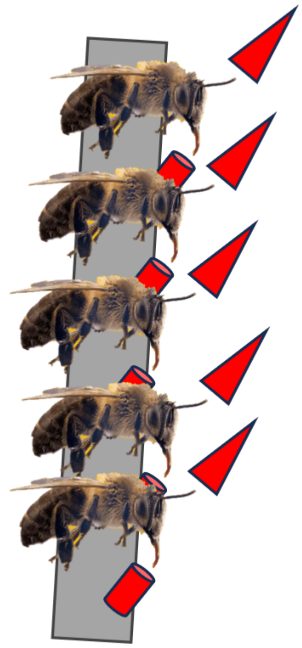


Figure 8.2.1: Rough Visualization of the Infrared Spectrum Optical Design.

The bees for the infrared spectrum section will be inserted along a vertically stacked tray, slotted into place with the infrared photodetectors aimed downward - directly in front of where the bees are. This idle increase in infrared radiation will be taken into consideration, but ultimately remain a concern for the final accuracy of the system - optimizations can be done once the design begins construction and testing.

8.2.1. Radiation Equations

Despite the seemingly simple design, the mathematics regarding the photodetectors and what they will roughly 'see' takes quite a few steps and makes use of certain facets of Geometric Optics. As such, explaining the necessary equations for the system is of use for the subsequent Optoelectronic design. First and foremost, however, we require a specific piece of data: the thermal radiation emitting from a bee. This, however, is a lot more complicated than at first glance.

The actual information - the radiance of a bee - is not a statistic we were able to find. As such, an estimate had to be developed in its place. Making use of available data and statistics of bees, alongside certain approximations and several equations, the following steps were taken.

First, the equation for Black–Body Radiation - which is thermal electromagnetic radiation emitting from or surrounding a body in thermodynamic equilibrium - is:

$$P_{Net} = A * \sigma * \varepsilon * (T^4 - T_0^4)$$

Where P_{Net} is the net Power Emitted and Absorbed, A is the surface area of the target, σ is the Stefan–Boltzmann Constant (~$5.67037442*10^{-8}$ W * m^{-2} * K^{-4}), ε is the radiative emissivity of the target, T is the temperature of the target, and T_0 is the temperature of the environment. As is, certain values have to be approximated or estimated based on given knowledge and values.

An average worker bee is between 1 and 1.5 centimeters, with the average width of a half centimeter [66]. As such, let us take a bee of 1.25 centimeters in length and a width of half a centimeter, then estimate the average surface area of a bee by treating it as an ellipsoid with the diameter dimensions of 1.25 centimeters by 0.5 centimeters by 0.5 centimeters. The approximate formula for the Surface Area of an Ellipsoid can be calculated using Thomsen's Formula, which is:

$$SA \simeq 4\pi * \sqrt[P]{\frac{a^P b^P + a^P c^P + b^P c^P}{3}}$$

Where a, b, and c are the three dimensions from the origin, and P is the error control factor; the common value for it is 1.6075, which will set the relative error to just about 1.061% [67].

By using this formula, we can calculate the approximate surface area of a bee. After some calculations, the resulting value for surface area had come to be about 1.63231704 square centimeters (cm^2). We can now set this aside and calculate the next variable: radiative emissivity.

The Radiative Emissivity of a material is a constant value which estimates the effectiveness of which it emits energy as thermal radiation. Outside of ideal circumstances, materials have an emissivity below 1, with the ideal emissivity being exactly 1. Humans and similar mammals have an emissivity of 0.95 [68]. Insect emissivity, however, is slightly more complicated by the different material makeup. After some thorough research, we came across a 1987 research paper that went through the full scientific process and subsequently determined the emissivity of honey bees to be between 0.955 and 0.99 [69]. Due to this being a range, we've taken the average between the two ends for the result of 0.9725.

The Internal Temperature of a bee is somewhat in flux, but we have a clear frame of reference. Western Honey Bees comfortably live in the range of ninety-five to one hundred degrees fahrenheit, or thirty-five to just under thirty-eight degrees Celsius. As such, we'll take the average between the two. The temperature of the bee for the sake of the estimate will be 97.5 degrees Fahrenheit, or 36.38889 degrees Celsius. As for Room Temperature, the simple solution is to use the existing International Organization for Standardization (ISO)'s value for room temperature, which is simply twenty degrees Celsius [70]. Converted to degrees Kelvin for the calculations:

$$T = 309.5389°K,\ T_0 = 293.15°K$$

Now, we can calculate P_{Net} to be 0.016159438762 Watts of Emitted Thermal Power, rounded to 16.15944 Milliwatts. With this, we can begin calculations regarding the bee's proboscis itself.

8.2.2. Radiance of a Bee Proboscis

The Net Thermal Power Emissions of the Bee, P_{Net}, is treated as the Radiant Flux of the Bee, Φ_e. However, we need more than that in order to calculate the energy specifically emitted by the proboscis. First, we will need an estimate of the size of the proboscis itself; this can be approximated with a cylinder of a diameter of two hundred micrometers and a length of a half centimeter, resulting in an approximate 'visible' area equivalent to that of a half-cylinder, not including the circular faces. The calculated surface area of such a region is equivalent to 1.570795 square millimeters.

This can then be used in conjunction with the Radiant Exitance of the surface - which we can calculate by using the Stefan–Boltzmann Law. The Radiant Exitance of a surface of a real surface is:

$$M_e = \varepsilon * \sigma * T^4$$

Where M_e is the Radiant Exitance of the Target Surface, ε is the Emissivity of the Target (~0.9725), σ is the Stefan–Boltzmann Constant ($\sim 5.67037442 * 10^{-8}$ W * m^{-2} * K^{-4}), and T is the temperature of the target (309.5389°K). Going through the calculations, the resulting Radiant Exitance is equal to 506.246794 Watts per Square Meter. Converted to more viable units, we get 0.506246794 Milliwatts per Square Millimeter.

Combined, we get approximately 0.79520993 Milliwatts of power radiated from the proboscis in the 'sight' of each of the respective photodiodes.

8.2.3. Optoelectronic Challenges

It may not be obvious from the values calculated, but there is real cause for concern regarding the low amount of power radiated by the bees. Hypothetically it should be doable, given that the initial point of research was done within labs using both thermal imaging and Laser Imaging, Detection, And Ranging (LIDAR), but making sure the system can actually 'catch' enough of the thermal reading to get a result is going to be complicated. There are, of course, a few ways to enhance that.

The simplest ways to make the detection easier would be using materials that tend to reflect light and heat - such as aluminum - in small quantities as an analog 'amplifier' for what the Photodiodes each see. They would have to be carefully placed and positioned as to specifically only amplify the bee proboscis once it extends outwards. However, the amplification this offers, while helpful, may remain insufficient.

Another method, one which was covered more in Section 6.1.5., are the optimizations for the photodiode circuit design. Particularly, the concerns there lie with minimization of leakage pathways and destructive signal interference from the passive electrical noise that can be produced by the photodiode's input voltage or the feedback resistor.

These three improvements can be used in tandem to maximize a clear input signal and minimize signal interference, but there is still the risk of inaccuracies or failed 'readings' of the bee proboscises. This, however, can be considered acceptable to an extent; the Infrared Detection System is not built for high accuracy, but high speed. So long that it remains semi-reliable, it will be sufficient.

9. System Fabrication

9.1 Fabrication of Parts and Assembly of The Component and Systems District

Although our system is marketed as being small, lightweight and compact it is not small enough to print in a single go on our 3D printing bed to get around this we have designed our system in to different apartments to better visualize and explain this we'll show an annotated sketch of out system color coating and labeling the different areas of the system.

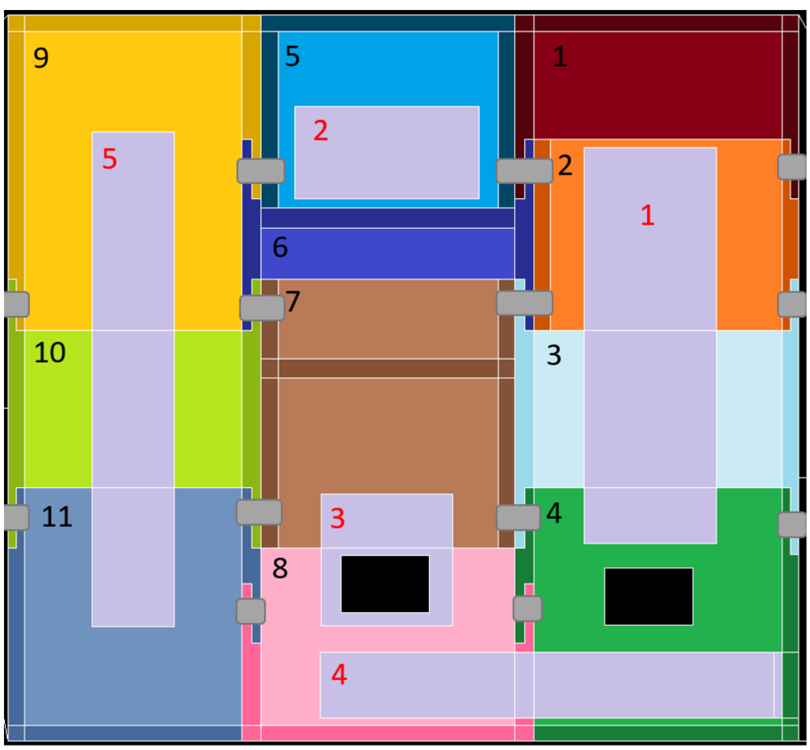


Figure 9.1.1: Visualization of The Component and Systems District.

Our system can be divided into three sections: the front air intake zone, the rear handle and display region and the currently shown component and system district. In this beautifully shown design each apartment has been color coordinated and numbered in a black text font for visual clarity and distinction for the reader. When looking at any of the apartments you'll notice darker hues of the color of each apartment this represents the walls and floors that are extruding towards the perspective of the viewer. Also in the sketch are 5 pale lavender colored rectangles numbered in red font. These are different system components that range from optical to electrical that we will get to as we talk about each system. And lastly the black squares are the bees that we are using to sense the explosive materials.

The component and system district section is then further divided into 3 columns going from right to left, the first of these columns containing apartments 1-4 is used for the visual light image detection system. To first start with this system we will began in apartment 4 looking at system component 4 this rectangle laying in both apartments 4 and 8 in actually a cylindrical tube that brings in air from the front air intake zone and releases it exposing the bees to the explosive materials that we hope to detect by imaging there response the pale lavender rectangles labeled 1 is the lens system and camera the takes up the entirety of apartment 2 and 3, apartment 1 is used for the electrical and digital connections to the camera from the battery to power it and then also send the visual data from the camera to the Microcontroller and AI dev board in apartment 5.

This now brings us to the top of column 2. In apartment 5 containing system components 2 are as mentioned both the Microcontroller and AI dev board. Below this apartment we have apartments 6 and 7 as you’ll notice these two apartment have white triangles intersecting then these represent smaller fans meant to direct the sampled air out of the bee detector apartments and funneled into apartment 5 to cool the the electrical processing components that is them dumped into column 3 that we’ll get to in a little bit. Now system component 3 residing in both apartments 7 and 8 is our infrared sensing system that is our less accurate but faster processing early warning system that uses our PCB stored in the front air intake zone. Finishing with column 2 and going to column 3 this entire section is solely used for the containment of the battery that powers our system and the last stop for our imputed air as the fan in the bottom of the section of apartment 11 shoots it out under the systems handle air. Lastly the small gray rectangles represent M4 screw holes that will be used to fasten the individual apartment together.

9.2 Assembly of The Front Air Intake Zone, Rear Handle, and Display Region

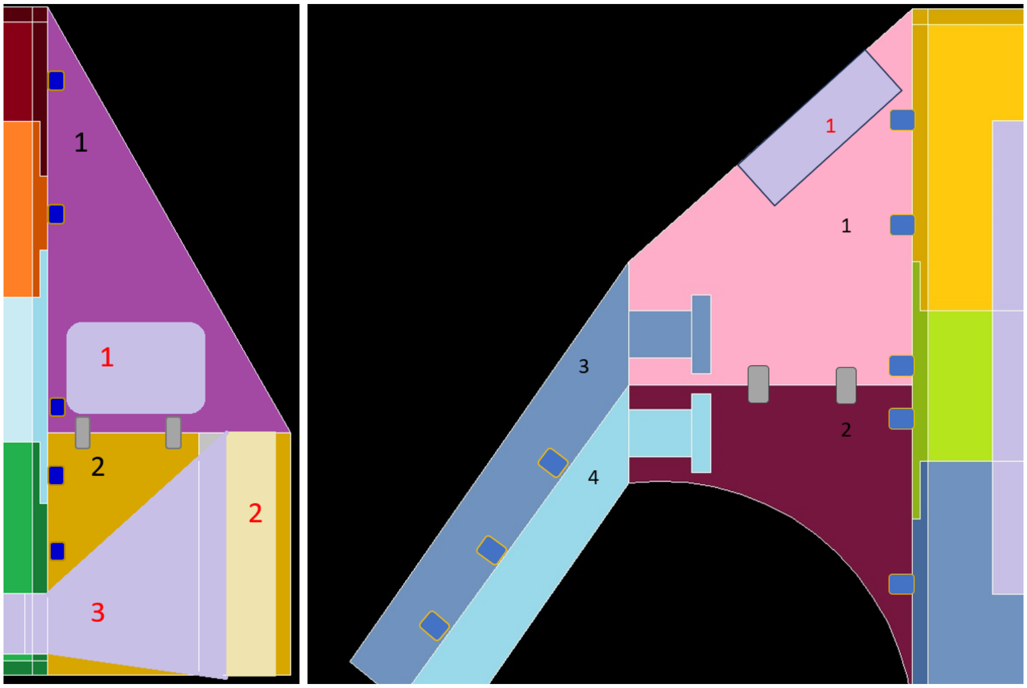


Figure 9.2.1: Visualization of the The Front Air Intake Zone and The Rear Handle and Display Region

This is the front section of our system titled the front air intake zone; it is to the right of the previous component and systems district that can be seen in the left section of the image. This section only has 2 apartments. First we will be starting off with apartment 2 looking and component 2 this is our high powered fan that will be sucking the air into our explosive detection system into system component 3 which is the same cylindrical tube that brings in air into apartments 4 and 8. Above apartment 2 we have apartment 1, which houses our PCB that will process the results from the infrared system in apartment 8 and 7 of the component and systems district.

Wrapping up this section, the gray rectangles are the same as last section that are holes for M4 screws to join apartments 1 and 2, lastly the new blue rectangles boarded in gold represent our heat set inserts the are metal threaded holes that get heated up and then squeezed in to precut holes made at the time of printing the part. These threaded holes will be joined by screws inserted through the walls of the apartments in the first column of the component and systems district.

Finally, the rear handle and display region of this section is pretty small and simple. In apartment 1 we have component 1 the LCD display. This display will be hooked up to the microcontroller and the PCB acting as a relay to tell the user the results from both the visual light system and the infrared sensing system and show how each bee has responded to the air sample. Apartments 1 and 2 are actually 4 parts that will be screwed together with M4 screw shown in gray to fully encase the slot joints that will support the handle of the device. Lastly heat set inserts will be used in apartment 3 to provide threaded holes to insert screws joining apartment 4 together with

3. The heat set inserts will also be used to join the rear handle and display region with the back most apartments of the component and systems district.

9.3. Bee Loading Tray and Harness

The below design is for the tray, which will be used to load the harness-wearing bees into the BEESTING device, and to hold said bees in place so that they will be in the most optimal position for imaging from the lens systems. The bee harnesses will be held in place by the black slots that correspond with the underside of the bee vices. To place this apparatus into the device we will be using a method similar to captive nuts where as the part is printing you stop the print to insert a component. In this case it is a magnet that will cause this module to instantly snap in place to where the machine learning programs have been trained to look at.

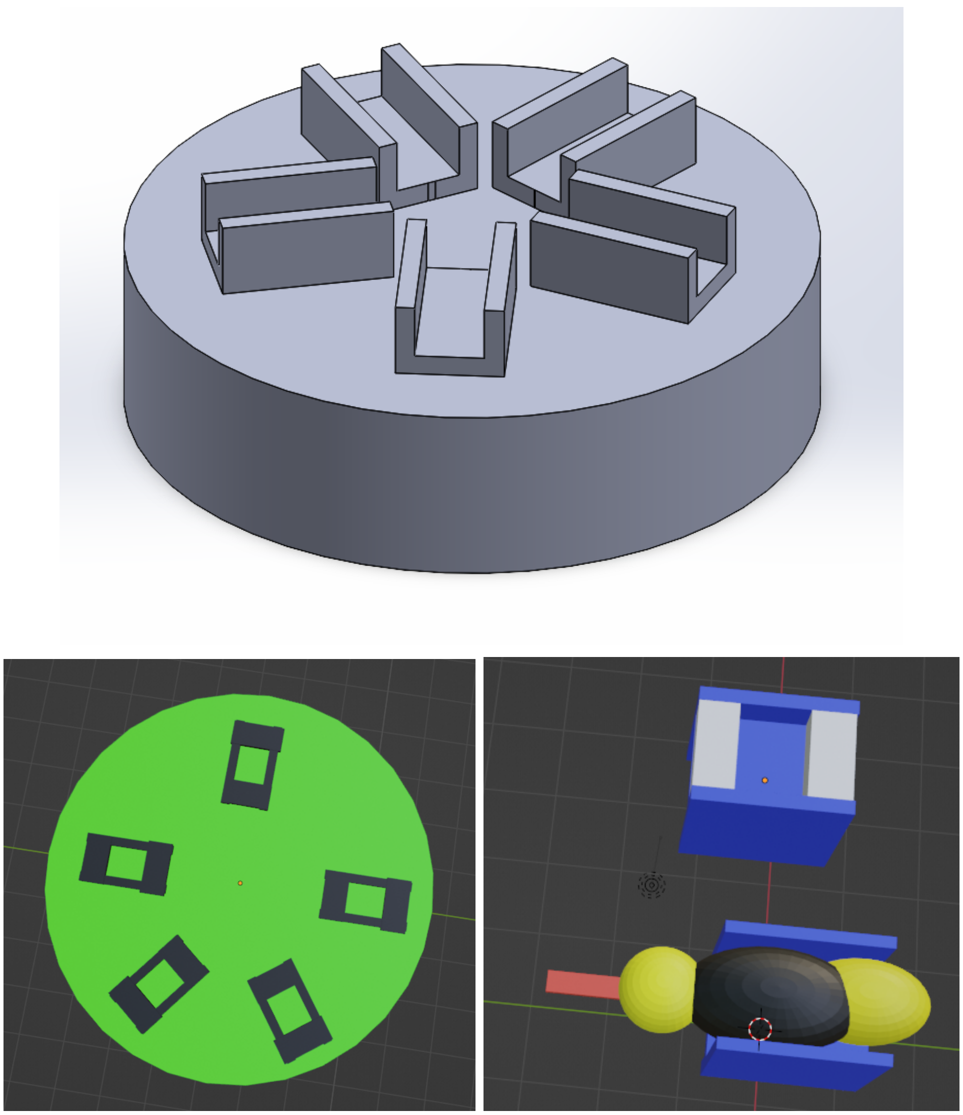


Figure 9.1.1: Models of the Bee Loading Tray and Bee Harness for use in the Visual Spectrum Chamber.

10. System Testing

10.1. Hardware Testing

Hardware testing will involve testing the individual hardware components as well as the PCB board with the components integrated into it. The NVIDIA Jetson Nano operating temperatures will be tested. During software testing, the temperature of the NVIDIA Jetson Nano will be monitored to make sure that temperatures are kept at a minimal level. This is to ensure the bees are not overheated and could die within the system. As the system runs its model temperature will be tracked with software that will be installed onto the board. Testing on the board will also be conducted once it has been implemented into the final design to check ventilation and to keep temperature at an optimal level once final design has been completed.

Testing the battery will be done following the standards, first the battery will be tested itself through means of charging and discharging the battery to keep in line with safety when testing the battery with the components. Temperature will also be monitored as the battery is used to power the components like the NVIDIA Jetson Nano and the PCB. To also test the battery life and exactly how long it will last, we will simulate by drawing power from the battery that is equivalent to what we will see from our system to check the reliability of the battery and temperature when operating at full capacity within our system. The battery will also be tested with each subsystem before final assembly is done to check the individual power needs for each subsystem. This is to also confirm that, in a practical setting, the battery has sufficient throughput for long-time use on the field.

Testing the PCB board will involve checking that all systems within it function correctly. To test the LEDs and to confirm that they will provide the correct amount of lighting, we will test the LEDs in line with the camera, NVIDIA Jetson Nano, and lens set up. To test that individual system, we will run tests by simulating an enclosed chamber with the LEDs on. This will first be tested with just the camera and the NVIDIA Jetson Nano to check if sufficient lighting is available for object detection and the camera. Once lighting has been tested and determined, next will be incorporating the lens. This will be achieved by checking the camera with the lens and testing the distances we have determined within optical design. For a successful test, we want all five bees that would be inside the chamber to be seen by the camera at once. Once this has been achieved, final assembly of the subsystem can be done and implemented into the overall device.

To test the infrared photosensors on the PCB, similar testing will be done. The infrared will be tested within a simulated environment as well. To do this, testing will be done in an enclosed chamber, similar to what will be done within the device. No lights will be on within this chamber to test the sensitivity of IR sensors and to determine exactly how much change occurs when a bee’s proboscis protrudes. This will be done by utilizing a tool of similar size and inserting it into the chamber to see how much the sensors change by.

To test switch and button implementation, the system hardware will be connected to the PCB and then tested with the battery. First the switch will be tested to check implementation and that the battery will only supply power to the device once the switch has been closed. This will then put the hardware into an idle state to wait for the button press. To test the button, first the testing of the executive tasks will be done to ensure that the tasks that are run once button press is done and are able to execute (discussed in software testing). Testing the button will be straightforward and will involve testing that the power is initiated in the devices and the tasks done by them are executed and produce a result.

Testing for airflow will be tested during construction of the housing device. Since our device will have fans that pull air in, we must first test the fans with our PCB and be able to maximize the speed at which they pull air in. If we have improper airflow within the device, it could lead to the bees not getting a proper scent or components overheating. Testing for this will first be conducted by pushing air through a prototype build of our device to test that it reaches through the device. We will also pull air into the chambers and to confirm that scents get there, we will spray scented air in front of the prototype while the fans are on. Once enough time has passed, we will remove the chambers and open them. If the scent can be detected from inside the chambers, then our airflow works as intended. Since none of us are experts on this we expect that testing for this will be extensive and require multiple iterations of designs to be achieved.

Another test will take place to check and make sure that the chambers can be placed inside the device comfortably. We must ensure that the chambers are properly fastened and fit inside the device to not create any problems. Some problems that can be created from an incorrect chamber could be that the detection systems do not identify the bees correctly. A loose chamber can lead to faulty and incorrect results. Thus we will be testing to make sure that every chamber we build will properly fit inside of the device.

10.2. Software Testing

Testing for software will be broken down into stages. Both the embedded software and the object detection software will be tested as development is conducted. For object detection the software will need to be tested as it is trained utilizing the F1 score as mentioned in design. Using the F1 score will determine the accuracy of the current iteration (0 being inaccurate and 1 being high accuracy) that is trained and whether more changes to the software need to be done. This will be done utilizing different dataset sizes for testing. Once a proper model is trained and can achieve at least eighty percent accuracy, it will then be loaded onto the board for further testing.

A table breakdown will be used for readability of testing and will manually be recorded to ensure that the trained model is optimized. To ensure that testing is done accordingly, certain factors will be recorded into the table such as runtime, the number of iterations, F1 score, and Precision will be emphasized the most. Depending on the parameter being tested, other parameters will be kept static for a baseline result on each parameter before changes are made for other parameters. The table itself will be more detailed once individual parameters are sorted. Once this is achieved testing will begin with altering parameters under each parameter that had the most positive effect on the training to increase the F1 score and increase the accuracy of the model while maintaining a lower runtime.

	F1 Score	Accuracy	mAP	FPS	Runtime	Number of Iterations
ReLU						
Parameterized ReLU						
GeLU (Will use more)						
Batch Size of 32						
Batch Size 64 (In full table more will be shown)						
Learning Rate = 0.1						
Learning Rate = 0.01 (More will be tested)						

Table 10.2.1: Table to determine which parameters lead to the best trained model. Will be revised in Senior Design 2 during development and testing.

Once the object detection model is on the board, testing will then begin with the camera and the NVIDIA Jetson Nano. Since this model is only detecting one object, this board itself will be tested as well. To do this another pre-trained model will be loaded onto the board and tested for basic detection to see exact output and possible FPS that the system sees when running the model. If the bees are ready for use at the time the model has been trained, then they will be used to test the actual model in real detection. To do this the system will be tested using a standard web camera placed close enough to a bee to detect their proboscis. This is to test the standard detection from the model before the microscope camera and the lens are integrated, and final integration of the device is finished.

The next step will be testing the connection that will occur between the UNO microcontroller and the NVIDIA Jetson Nano. To test that the connection works as intended and that the I2C connection works as intended, we will pass simple data between the two boards to see if the NVIDIA Jetson Nano returns the data requested as intended. Since the input data of the NVIDIA Jetson Nano will only be connected to the camera and running object detection, the output data indicating the results will be passed to the MCU. This is why the data that is passed to the MCU will be tested by first passing standard requests and responses to ensure communication between the two devices. Once this is confirmed the data will then be passed to the LCD display from the MCU.

Testing the MCU will involve testing the communication protocols that are utilized with the other systems connected to it. Testing the IR sensors with MCU will be done by first checking that the IR sensors return changes in lighting. The IR sensors will be implemented into a chamber with no light, but for testing purposes we will be checking to see that they are able to detect slight variations in luminosity. To do this, we will simulate similar conditions to the dark chamber and just conduct passes over the sensors to first check detection. Following that, we will then use small objects, i.e. a bobby pin or similar, and move them past the sensors to simulate what would be the bee’s proboscis. Simulating this will allow us to represent the conditions as close to what we expect once inside the chamber.

To make sure all embedded systems are working correctly, as the communication for them is coded, checks will be done to ensure that the master and slave integration is working as intended between the different devices. This will be done in a similar manner like that of the NVIDIA Jetson Nano, but SPI will be implemented for the communication between all other devices. In order to test the SPI connection and to ensure that data is being sent and received correctly, a simple loop of data will be sent back and forth between the devices using POCI to PICO. This means the data sent will be the data that comes back so that we see the connection works as intended. This test will be done between all the peripherals connected through SPI including the LCD.

Testing of the LCD display will be conducted as developed. This will be done by first using test values to see if it is properly output to the display. Making sure that the display is readable for the user is important while also making the output data easy to understand. Once the user display is formatted, then testing will begin with passing actual data to the display from the two subsystems. This will also be tested by passing different instances of data to ensure all output that is expected or can be expected, is displayed correctly to the user. Once all the software for each subsystem has been thoroughly tested, each system will be combined and integrated then tested together. Testing will occur with test data until bees are acquired and test data will be then switched to live testing with the bees and software for both detection and communication between devices.

More simple software testing will include the LEDs, fans, button, and switch. All of these peripherals will be tested in the same manner. To make sure each peripheral is working as desired before they are implemented into the PCB, we will test them using a breadboard. Each peripheral will be connected to a breadboard, along with the UNO R3, and tested to see if the SPI communication is working properly. We will be using code programmed into the UNO R3 to carry out each test. For the LEDs we will test to see if the red and green colors work and check the luminosity for each. For the fans we must check to see the fan speeds that are adequate enough to control air flow through the system. To test the button and switch we will be using help from either the LEDs or LCD to determine if the UNO R3 is receiving proper input.

10.3. Biological Sensor Testing

Once fully trained, the bees will undergo a series of tests to ensure they were properly trained and able to function as expected in the device. The test chemical the bees were trained to detect will be sprayed onto several objects. Since the purpose of the device is airport security, these objects will be hidden in backpacks or suitcases that are marked accordingly. Other items in the set will not contain the chemical substance. After this, the device will be used on the set of luggage and the accuracy of the bees will be assessed. This test can be repeated with differing amounts of the substance hidden in the luggage to better test the bee's sensitivity. In the event of a malfunction in another part of the device, the bees can also be assessed independently.

10.4. Optical Testing

The testing for the Optical Systems will be split across the two Optical Subsystems, as each system has fundamentally different designs and concerns that would need to be considered and addressed.

10.4.1. Visual Spectrum Testing

For testing of the Visual Spectrum system, after assembling the system based on our predetermined and simulated placements for the Lenses and the camera, we simply position the camera and observe. The image created when testing we were able to observe this image:

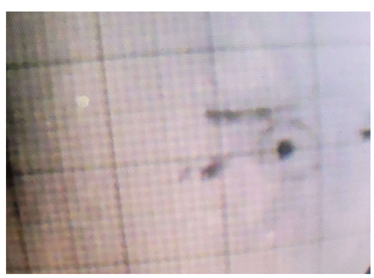


Figure 10.4.1.1: Image taken from Visual Spectrum Optical Test.

The black dash is representative of the average size of a North American Honey Bee's proboscis of which we are trying to image. An important thing to note is that when conducting this test, we were limited when it came to both the available components and the positioning of said component. Without our desired Lenses and using an optical rail, we were not able to get all of the optical components into their exact position. As such, the test design was off by two to five millimeters. This has resulted in a slightly blurred image during testing.

This will be fixed by using the intended lenses, which will be fitted to the Lens Housing Unit that we will have milled and produced by mid-September during Senior Design 2.

10.4.2. Infrared Spectrum Testing

The key points of testing when it comes to the Infrared Subsystem will be threefold. The first is testing the Photodiode and the connected circuit to confirm it works as intended. The second is confirmation that the Photodiode can reasonably detect a bee's proboscis in simulated observations. The third is confirming this all works in tandem with a multiplexer and on the Arduino UNO R3 Microcontroller.

The first test, determining the Photodiode and circuit work as desired and intended, is one that would require a multitude of both simulated and practical tests. Observing the base level of noise the Photodiode produces in a near-lightless environment, observing the effectiveness of the Transimpedance Amplifier in curbing Parasitic Capacitance and Johnson-Nyquist Noise in said environment, and adjusting the resistor and capacitor values until the cleanest signal comes through will be an arduous set of tests and re-tests. Doing it purely from a design standpoint is infeasible, as there are multiple elements that most student-accessible simulators cannot properly represent; it requires a practical environment for the tests to work best.

The second test, confirming the ability to detect the bee's proboscis beyond the mathematical calculations, is one that also requires practical testing and adjustments. This would require direct interaction with bees, as the device will specifically be searching for the electromagnetic emissions radiating from the bee proboscis. The bee will have to be placed into the same near-lightless environment as used for the first test. From this, we can record the received signals as samples for further testing.

The third test, confirming the effectiveness of the Multiplexer and Arduino UNO R3 Microcontroller, can be done with the received and recorded signals from the second test. By mimicking the recorded signals, we can do a multitude of tests to adjust the received readings by the Microcontroller.

10.5. Overall integration

The overall integration of the system will occur once testing on the individual subsystems and integration of subsystems is completed. This means that the device will have a readable LCD display for the user with a simple switch and button activation. The switch will turn the device on while the button will activate all the tasks the hardware and software will execute. Ideally the end result will be a 3-D printed device with no major hardware components visible to the user. It will have chambers that can be removed to change out the bees and a removable battery as well.

For the housing of the device, parts will be 3-D printed as stated and assembled together with the hardware components. Ideally for wiring the device will have space on the side to run wires to each component throughout the device including the fans, LCD display, Jetson Nano, and other peripherals within the device. While assembling the final device the components will first be connected and tested. The printed device will be assembled in sections with hardware components being integrated with mounts that will be 3-D printed in the sections needed. Once hardware is and fans have been added, the rest of the housing unit will be assembled with chambers removed from the device. Chambers will be fitted into the device once bees are obtained.

10.6. Plan For Senior Design 2

The plan for Senior Design 2 will be broken down into three main groups.

First, fully fleshing out and fine tuning our methods and procedures for training the bees to make it as efficient and effective as possible. This may involve making adjustments to the bee-holding cartridges, as they were designed to work with the average size of the North American Honey Bee. Additionally, we may end up developing different sized mounts to hold bees of different sizes in the case this becomes an actual problem.

The next group involves training the AI Development Board and Machine Learning Algorithm so that they can accurately identify the response from the bees; the response that we desire during this process is when their proboscises are out. This will be done by manually feeding the Algorithm images and informing it whether the image has a bee proboscis or not, then letting the Algorithm do its own ‘checks’ with human oversight until it becomes capable of doing it on its own.

The final group will be focused on optimizing our design to achieve all the requirements that we have put upon ourselves. This may include redesigning our Subsystems, both software and hardware.

11. Administrative Content

11.1. Milestones

Milestones for the project need to be set in order for a smooth completion of the project. To keep in line with these Milestones, individual deadlines are to be set so that falling behind does not occur. Currently certain deadlines have been missed, which has led to delays and certain issues arising. That being said, deadlines for Senior Design 2 will be more strict, and a checks and balances system will be implemented to ensure that these Milestones are finished in line with our personal deadlines ahead of class set deadlines. This checks and balances will involve peer reviewing work from other authors to ensure work is being accomplished and if problems are arising they can be solved together as a group to adhere to our deadlines and Milestones.

Tasks	Start Date	Planned End Date	Final End Date
Divide and Conquer Documentation	5/18/2023	6/2/2023	6/2/2023

Tasks	Start Date	Planned End Date	Final End Date
Divide and Conquer Documentation Revision	6/2/2023	6/9/2023	6/9/2023
Core Component Selection	6/9/2023	6/7/2023	6/30/2023
Initial 60 Page Documentation	6/9/2023	6/30/2023	6/30/2023
60 Page Revision	5/18/2023	7/12/2023	7/12/2023
120 Page Rough Draft	7/12/2023	7/23/2023	7/23/2023
120 Page Final Document	7/23/2023	7/23/2023	7/25/2023
Senior Design One, Final Submission Deadline	7/25/2023	7/31/2023	7/31/2023
Sub-system Design	6/2/2023		7/25/2023
Sub-system Testing	6/2/2023		7/25/2023
PCB Design	6/2/2023	TBD-Senior Design 2	TBD-Senior Design 2
PCB Testing	TBD-Senior Design 2	TBD-Senior Design 2	TBD-Senior Design 2
Prototyping	TBD-Senior Design 2	TBD-Senior Design 2	TBD-Senior Design 2
Completion of Final Prototype	TBD-Senior Design 2	TBD-Senior Design 2	TBD-Senior Design 2

11.2. Initial Budget Estimations

As of this moment, the estimated budget solely contains hardware that is still either unselected or tentative - our selection of software is fortunately covered by the university - leaving the final available estimations to be rougher than what we would like.

Considering the costs of the cameras, optical lenses, AI board, microcontroller, 3D printing filaments, LEDs, LCD Display, Fans, and wiring, we are looking at a rough budgetary cost of over seven hundred and eighty dollars ($780.00). The most expensive parts of this lab are the

Power Supply, the Microcontroller Board, and the AI Development Board - roughly two hundred and fifty dollars ($250.00), one hundred and seventy dollars ($170.00), and one hundred and fifty dollars ($150.00) respectively. Then, as for the remaining technologies, there are the three lenses - costing around another one hundred and sixty dollars ($160.00) in total, and the PCB, LCD, and LEDs - which will field additional costs over fifty dollars ($50.00).

11.3. Bill of Materials

Part Name	Manufacturer	Part ID	Quantity	Cost
RGB Led	DIALIGHT	350-5218559F-ND	15	$16.19
LCD Display	MikroElektronika	932-MIKROE-4	1	$40.88
Photodiode	LUCKYLIGHT	LL-503PDD2E	10	$20.64
AI Development Kit	NVIDIA	945-13450-0000-100945-13450-0000-100	1	$166.79
CMOS Camera	AmScope	MD310C-BS	1	$181.04
Lens (BiConvex)	ThorLabs	LB1811	2	N/A*
Lens (BiConcave)	ThorLabs	LD2568-B	1	$169.98*
Microcontroller	Arduino	A000066	1	$27.60
Multiplexer	Texas Instruments	CD74HCT4051E	5	$10.56
Shift Register	Texas Instruments	CD74HC595E	3	$4.08
3D Printer Feed**	Overture	ABS Filament	1	$21.00
EST. TOTAL				$658.76

**ThorLabs product cost is combined due to fees and shipping costs. **Cost is estimated based on the whole reel.*

11.4. Table of Work Distributions

Job	Field	Primary Worker	Secondary Worker
Website	Computer Science/Engineering	Cole Correa	
3D Design/Printing	CADD	Nicholas Johnson	Hussein Shelleh
Visual Spectra Optical System Development	Photonic Science/Engineering	Nicholas Johnson	
Infrared Optical System Development	Photonic Science/Engineering	Hussein Shelleh	
Bee Training	Biology	Nicholas Johnson	
Device Wiring	Electrical Engineering	Hussein Shelleh	Cole Correa, Trevor Van Baulen
Machine Learning Development	Computer Science/Engineering	Cole Correa, Trevor Van Baulen	
Embedded System	Computer Engineering	Cole Correa, Trevor Van Baulen	Hussein Shelleh

12. Conclusion

The BEESTING project is one that works with a handful of disciplines and a variety of skills. Some within the project's existing group and purview, and others requiring some assistance and practice we otherwise would not have tried. In other words, this project has been a fairly significant learning experience to us all, and it's not even halfway over.

We are a team of two Photonic Science and Engineering students, and two Computer Engineering students, with one of the former pair dual-majoring into Electrical Engineering. While the fields themselves are fairly clumped together and closely related in certain aspects, much of the actual device work had initially been split firmly in specific places in order to focus on our existing strengths. However, as time continued on, inter-disciplinary discussion amongst ourselves grew, and we came to learn about more as a result.

Our skills, too, have grown and improved. Much of what we are doing within the BEESTING project - or at least, what we intend to do - are things that we have yet to do ourselves, pulling much out of the way of theoretical and entering practical feet-first, hitting the ground running where and when we can to try and learn the skill and apply it simultaneously in the name of success. In some cases, this has already borne fruit; a few things in this very paper are skills that some of us have never used before, but found great use in here.

The initial writing was daunting for the group, but we were confident from the beginning that we should be able to pull through - so long as we all did our part and completed what needed to be done as best we can. This tested our willingness to trust and cooperate, something that often was left to the wayside during most of our degree path; the primary reason our group came together so quickly were the existing connections each of us had. It would be fair to say that we ended up better for it, learning to make use of the common goal and assisting one another to the best of our abilities over the nearly three months we've been together.

All of this has culminated in what will become the BEESTING. Optical designs, machine learning algorithms, embedded systems, 3D printing, and more all planned to come together into a singular handheld design, one with the sole intention of detecting target chemical compounds in the air via the usage of bees. A cheaper solution to animal-based bomb or drug detection, and a more effective one than similar-cost technology. Through it, a more effective tool to help keep people safe can be shared and developed.

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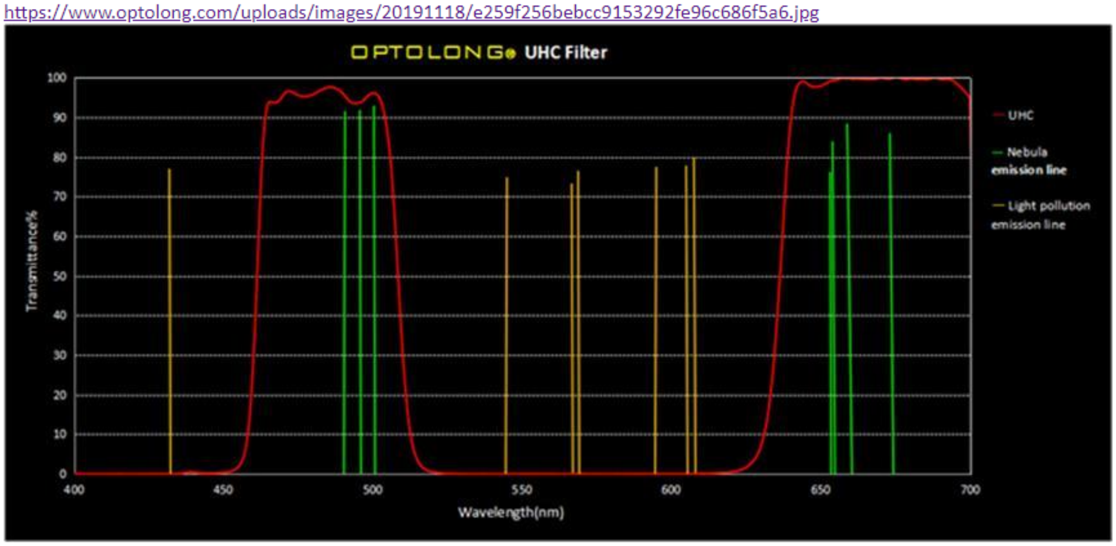

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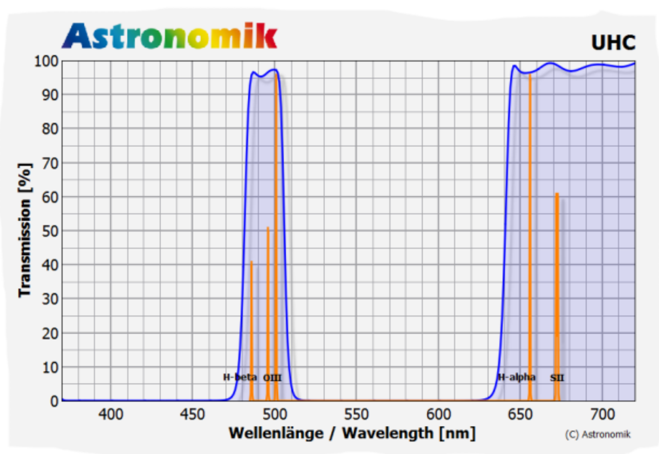

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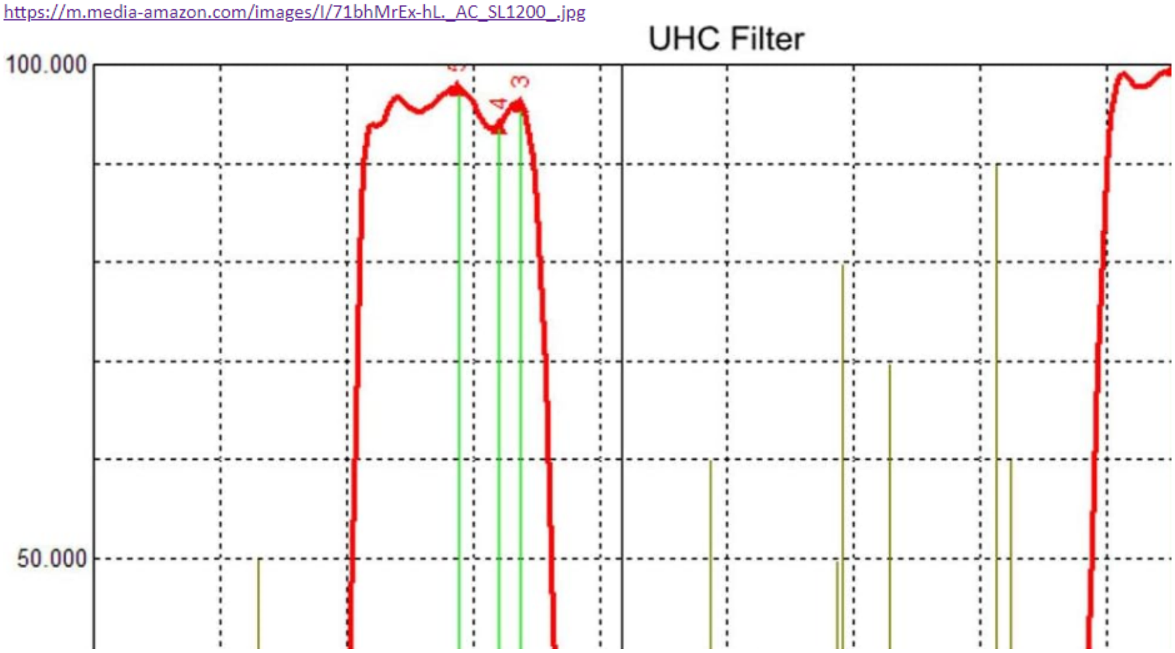

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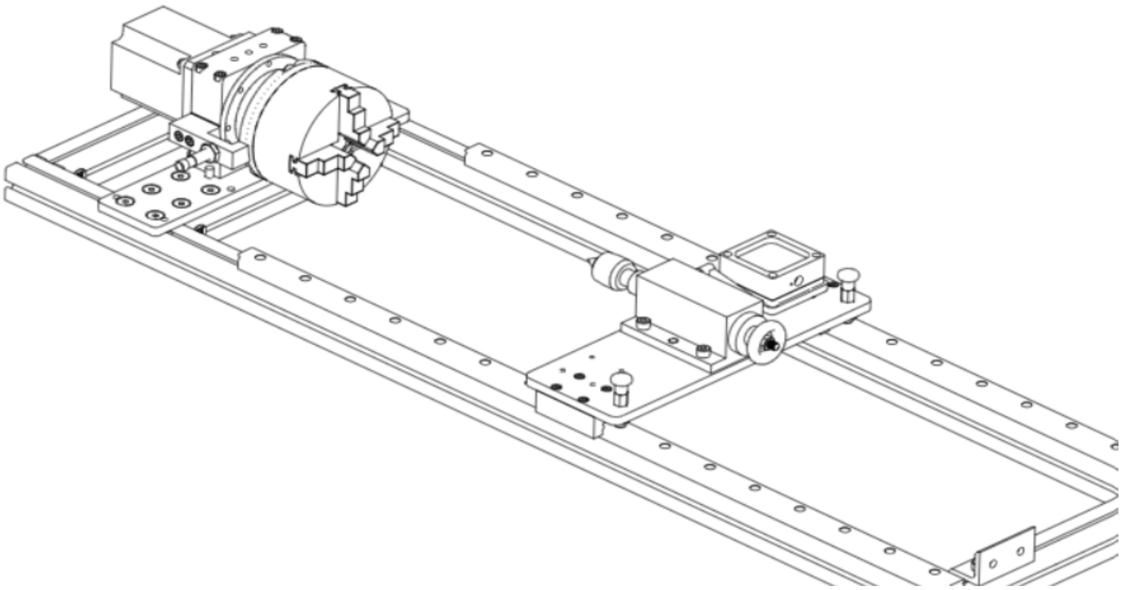

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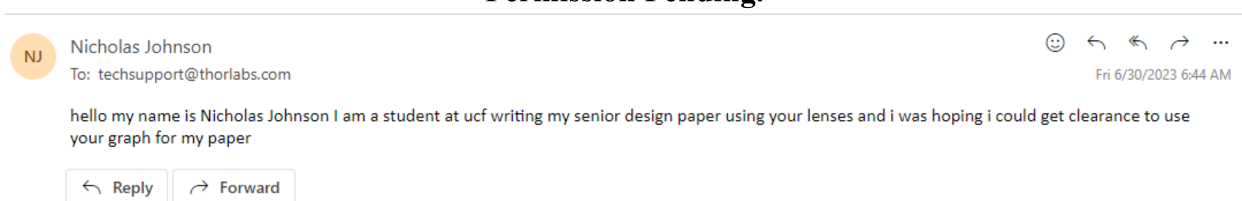
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