# Detecting Explosive Material via Optical Systems Observing the Behavior of Bees

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***Abstract* — A project based on the developments of Los Alamos Lab, the Bee-Enabled Explosive Substance Tracer and Identification of Narcotic Goods (BEESTING) is a creative attempt at using the observed results of the lab's prior work with using bees for bomb detection purposes. This project intends to make use of the strong olfactory sense of bees in order to detect a target compound. The bees are observed in an enclosed device with image object detection and infrared motion sensors in order to facilitate easy use of the bees, all without requiring direct and careful handling.**

***Index Terms* — Bees, bomb detection, imaging system, infrared motion sensor, neural network, object detection.**

## I. Introduction

Bomb detection technologies are varied, each with unique advantages and disadvantages respective to their methods. However, bomb detection tends to either be limited in scope, be notably expensive, or require significant time investment for training. Dogs take years to train, and advanced machines take months of practice for sophisticated use - not to mention the cost of either of these options. Using bees, however, can allow for a cheaper solution that still accurately detects target chemical compounds.

With this in mind, the BEESTING device 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. Of course, lacking clearance for illicit substances, this system will be tested via 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.

## II. Bee Training

As the name of this project implies, the most important aspect of a bee-based detection device is the bees. With tens of thousands of types of bees across the globe, each with their own unique characteristics, the choice in which bee can become very difficult. With different species having varied levels of vapor detection, different levels of aggression and widespread availability, it took a careful process of selection. Apis Mellifera - commonly known as the western honey bee or European honey bee - was selected.

### *A. Bee Selection*

It is critical that all bees are selected from the same hive / colony; if not, bees from different colonies may become hostile with each other or cause undue stress to each other, which would reduce their working efficiency. Around 20 to 30 bees are captured from the hive, then they are gradually chilled to around 50-55 degrees fahrenheit. This slows the metabolic rate of the bees, making them easier to work with. Bees with the preferred size preferences are then strapped into specialty 3D printed harnesses, and the rest are released.

Following this is the second round of selection, where we test to see whether or not the bees have the ability to extend their proboscis. A proboscis is a long and tongue-like tube that is used for eating and gathering nectar. The ability to do this is essential to the device as the proboscis is the target that we are imaging to see if they detect any explosive material. To do this, a cotton swab dipped in sugar water is placed in front of them; if they stick their tongue out then they pass to the next stage of training.

### *B. The Pavlovian Response and Bee Intelligence*

This part of the training involves repeated exposure to a specific chemical / scent, immediately followed by a sugar reward. The principles behind this process are entirely based on the techniques and theory behind training bomb dogs. During the training, the bees will be continuously exposed to a highly concentrated explosive vapor for 6 seconds, then during the last 3 seconds a cotton swab soaked in sugar water is given to them. This will cause them to extend their proboscis, 'tasting' the vapor with the sugar water. By associating the scent with the reward, the bees will be conditioned, to extend their tongues whenever they detect the vapor the same as how a dog will sit when told. Following training the bees will be able to detect the train vapor at concentrations around 100 to 250 times lower concentration than what they were trained on; this will vary based on the chemical trained on based on its size, polar group and the volatility of the compound. The conditioning will become stronger the more this process is repeated with the bees and will typically take 2 ½ to 4 hours for each group of bees. After several hours the bees will be tested without any reward and if they have a high enough detection rate they will be inserted into the device.

### *C. Animal Protection Laws*

The Animal Welfare Act, passed in 1966 regulates the treatment of animals in laboratory environments. Under the current version of the law all warm blooded animals aside from mice, birds, and rats are protected from undue pain and poor living conditions. However, the law defines an “animal” as “a vertebrate other than man”. This means that anything lacking a backbone and a central nervous system are not afforded any protections under this law. Although we still do have to follow The Code of Federal Regulations (CFR) / Title 7 / Chapter III / Part 322 pertaining to the traffic and transportation of bees. As long as the bees stay within the same zip code / region and are all adult live honey bees we only need to worry about the laws pertaining to part 322.16 Packaging of shipments of the CFR.

## III. System Components

Our device consists of many components and subsystems. Some of the components are purchased while others were designed. This section will cover the main system components that were put together to build our project.

### *A. Printed Circuit Board (PCB) / Microcontroller*

The PCB for this project is designed with the ESP32-S3-WROOM-1 microchip. We decided to use this chip because of the large amount of general-purpose input/output (GPIO) pins that it provides. We needed a chip with many GPIO pins because of the wide variety of peripherals within the device. Other components that comprise the PCB are the multiple shift registers, multiplexer, resistors, capacitors, buttons, linear voltage regulator, and mini-USB port.

### *B. NVIDIA Jetson Nano*

The NVIDIA Jetson Nano Development Kit-B01 is an artificial intelligence development board that is used to control object detection within the optical sub-system of the device. The NVIDIA Jetson Nano will work with a CMOS microscope camera–details further in this section–and operates through the visual spectrum with a custom lens. The board itself utilizes a GPU 128-core Maxwell at 472 GFLOPS and a CPU Quad-core ARM A57 that runs at 1.43 GHz which allows for optimized speed of the object detection model. The device holds 4 GB of memory which allows the device to idle as the software runs waiting for the button press from the PCBs end.

### *C. Power Supply*

The power supply for this device is a fifteen-volt, six-point-six ampere battery with over an hour of operation time. This is perfect for our uses and power needs. Standalone, however, it is firmly unusable. This is due to the connection port’s shaping, as well as the voltage and amperage being too high for safe use. As such, careful wiring and voltage regulation is outright required to remedy this.

### *D. Voltage Regulator Printed Circuit Boards.*

There are two voltage regulators found in the device. They both utilize switching regulator components. The voltage regulators create two separate power rails - a five-volt rail and a three-point-three-volt rail - that will be used to power various components in the device. The former rail is directly connected with the power supply, and the latter rail pulls its input voltage from the five-volt rail.

### *E. IR Sensors*

There are five infrared motion sensors within the device. Each sensor is intended to detect the extension of the bees’ proboscises, then subsequently send a signal to the microcontroller. These sensors are fairly small on their lonesome. However, they require a small plastic cap on top of it in order to diffuse the infrared signal; said cap is included with the sensors.

### *F. Camera*

The camera we are utilizing is the Alvium 1500 C-120. This camera utilizes MIPI CSI-2 connection which is done through one of the two MIPI CSI-2 connectors available on the Jetson Nano. The camera runs at a maximum of 52 frames per second (FPS) with 1.2 Megapixels (MP). The resolution is 1280 x 960 and operates with a global shutter. The camera will be mounted on the top of the second chamber with the lens for it.

### *G. Lens*

The chosen lenses are 2 Thor labs LB1811 and 1 Thor labs LD2568. These lenses were chosen based on their focal length transmission, cost as well and their material characteristics. Both lenses are made out of N-BK7 glass which is known for its high clarity, low distortion and high refractive index homogeneity. Furthermore, it has excellent uniform transmission of the visible spectrum which is extremely important in applications where color reproduction is important such as this one.

*H. Fans*

Throughout the device, there will be three fans to regulate airflow. The fans we will be using are the Noiseblocker blacksilent micro fans. Each fan will have a diameter of forty millimeters or less. This restriction is in place because of the dimension constraints within the device. In addition, the noise level of the fans were taken into account, so as not to aggravate the bees inside. Each fan outputs fourteen decibels of noise. The fans will also help keep the bees cool throughout the process.

*I. Light-Emitting Diode (LEDs)*

One of the ways we will demonstrate the output of our device is by using RGB LEDs. The visual representation output will utilize ten RGB LEDs. The LED will either light up green or red depending on the results from each system. Five of the LEDs will be connected to the infrared system, and the other five will be connected to the visual spectrum optical system.

*J. Liquid Crystal Display (LCD)*

Another way we will demonstrate the device's output is via a LCD. The LCD will provide the user with a clear and easy to interpret output of the results. Said LCD will be connected with the microcontroller, given the final product of the data obtained and organized within the BEESTING device itself.

*I. Light-Emitting Diode (LEDs) for illumination of bees*

Actually seeing the bees can be frustratingly difficult in a closed system thanks to the evolutionary advantage of the fur that coats the bees' bodies. Regardless, this results in a very low reflectance of light in the visible spectrum of bees.

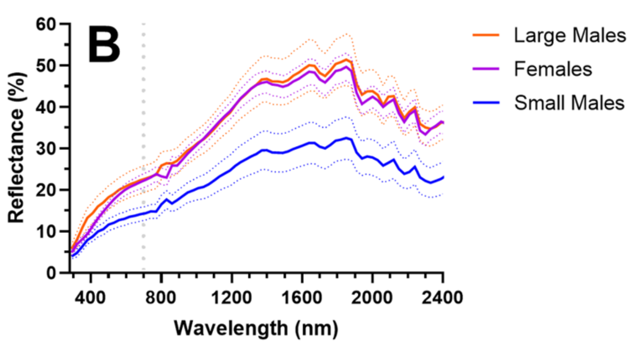


Fig. 1. Reflectance of a bee. *[1]*

Such a high reflectance causes a few problems for us, as the target wavelength that we want to image the bees at is between 600 nm - 680 nm. The reason we're targeting this range is because they are the colors of the bees tongue - which can vary throughout the day based on their hydration.

However, with only a reflectance of around 23%, this is problematic. The problem is compounded by the fact that our lenses only have a transmission of 92% in our target wavelengths, which means that only 77.87% of the light entering the lens system is actually transmitted.

92 77.868

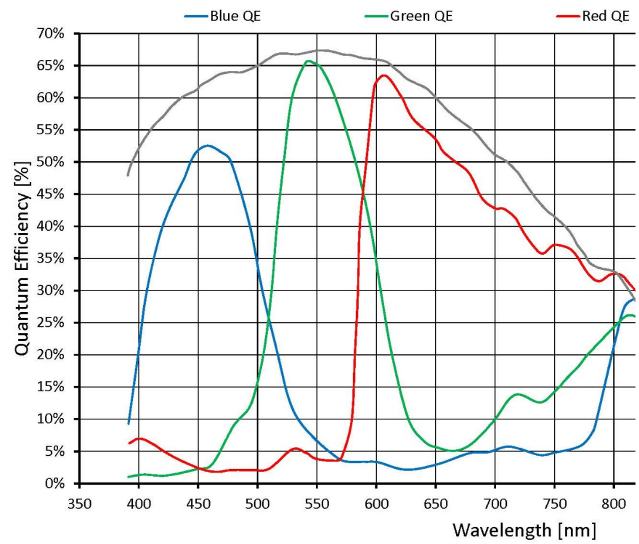


Fig. 2. Quantum efficiency of the Alvium 1500 C-120 camera. *[2]*

Quite tragically, the quantum efficiency in our target wavelengths of our camera is only 65% - 55%. Compounding all three of these factors, for every 1000 lumens shined on the bee, only 117 lumens are received by the imaging sensors. With the use of a spectrometer data was collected in the imaging plan and object plan with the illumination of a quartz halogen lamp at an illumination of 1750 Lumens 5 cm from the bees head, and another one targeted behind the the bee back lighting it at 480 lumens to increase contrast and image clarity of the bee.

Based on the calculations from this data, we determined the LEDs and for the job, as well as the positions and power. NTE Electronics, Inc LED NTE30043 was selected to do the job, with the front LED operation at 48 mA and a forward voltage of 2.1V towards the front of the bee and another one at 20 mA and forward voltage of 2 V passing through a 2.5 ND filter.

## IV. Hardware Systems

The device is constructed to contain two main chambers. Each chamber will consist of one main hardware system: the infrared (IR) sensor system and the optical system. Another system found in the device is the fan system, which exists to help control airflow. Finally, there are the printed circuit boards (PCBs) of the device. This section will provide in-depth and concise descriptions of each system.

### *A. IR Sensor System*

The infrared system is made up of the five infrared sensors themselves and the microcontroller reading them. These sensors are motion-based, and are better known as passive infrared detectors (PIDs). PIDs measure the difference in temperature in the air, with the average temperature in its entire view considered the 'normal' temperature. Once they detect a difference significant enough, the sensors send an electrical signal.

distinguishable. This is because bees can come in all shapes and sizes, with a height of 3-5mm and a tongue that ranges from 5.27 - 7.68 mm.

Even though the bees movement is restricted by the harness, the bees still have a noticeable range at which they can rotate their head and between the difference in the possible heights of their heads influencing the possible distance from the lens system by around 2 mm if their tongue is extended perpendicular to the imaging plane. but based on the degrees of freedom they have with their head and the length of their tongue that can be extended in different angle also reducing the imaged area, we need to be able to get a clear image of a tongue at 6 to 7 mm toward the lens and away from the lens system at the focal point.

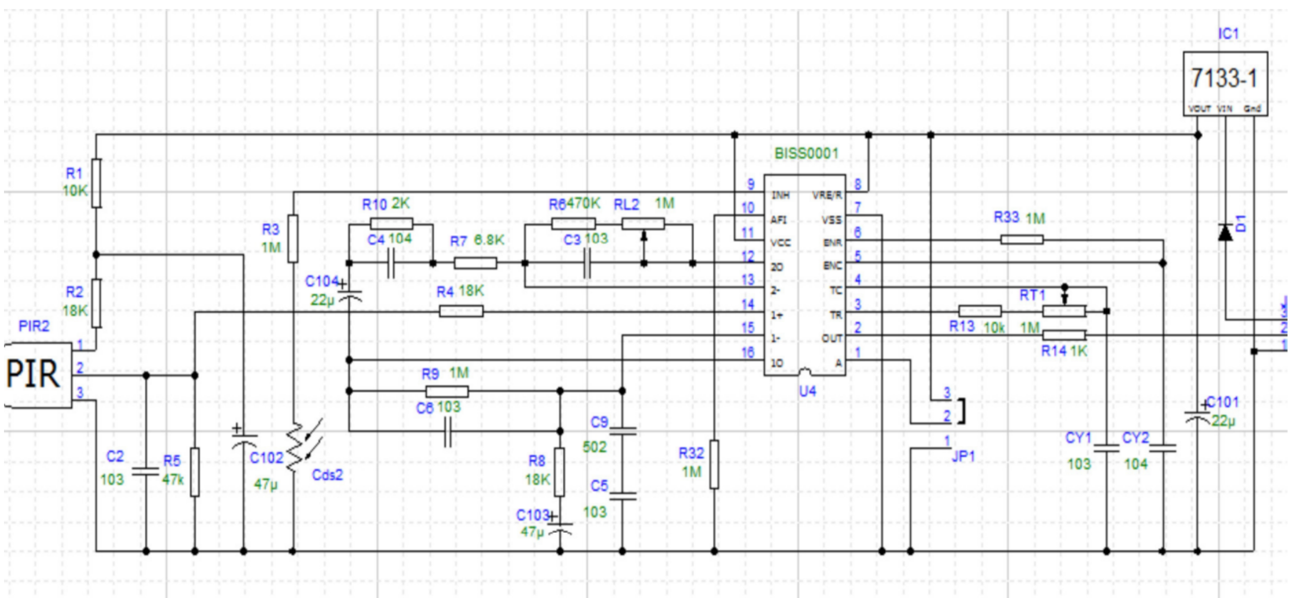


Fig. 3. PID circuit schematic. *[3]*

The PIDs, once adjusted within the confines of the device, will only have the ambient temperature and the motion of the bees to perceive. When the bees extend their proboscises, these sensors would be able to detect the shift in temperature, which results in an electrical signal being sent to the microcontroller to then relay to the eternal LEDs and LCD.

### *B. Optical System*

The sole goal of the visible light optical system is to be able to perfectly reduce the size of the imaged object area to as close to the exact size of the active imaging sensors of the camera with an image that is as optically clear as possible, but that also has a wide range from the focal point at which the image of the object is still


Fig. 4. Images taken of a dead bee at various distances.

### *C. Fan System*

The fan system is made up of three micro fans. The first fan will be positioned at the nozzle of the device to bring air in. The next fan will be located near the middle of the device between both chambers. The final fan will be at the exit vent of the device found at the rear. The front and middle fans will start after the button of the device is pressed. These fans will remain on for about a minute to regulate airflow throughout the device.

After a minute has passed, the exit fan will start and stay on for thirty seconds. The exit fan does not turn on immediately after the button is pressed because it would guide the stimulated air out of the device, which is not desired. Overall, the airflow will start at the nozzle of the device and circulate through the device, until the exit fan starts to remove the stimulated air from the device.

### D. PCBs

This device uses three separate printed circuit boards, all of which being fairly small in scale. This is both due to the inherent size limitations of the device, and to minimize points of failure in the case something either was designed improperly or had gone wrong in testing. Two of these boards are voltage regulation boards, and the third is the primary board itself.

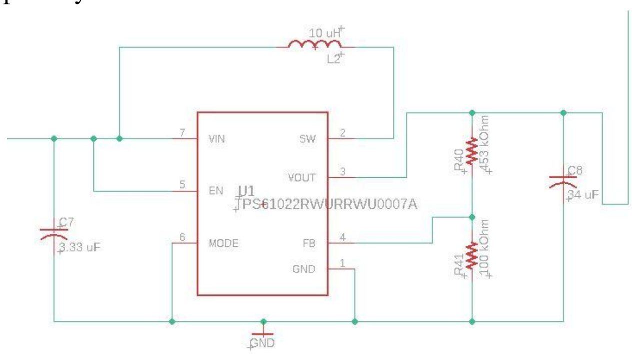


Fig. 5. Circuit schematic for the 5-volt to 3.3-volt voltage regulator.

The voltage regulating boards are fairly simple. The larger 15-volt to 5-volt regulator board is 40.3 mm * 27.9 mm, and the smaller 5-volt to 3.3-volt regulator board is 27.9 mm * 17.4 mm. These boards, specific to our needs, chain from the power supply to the main circuit board. In the case they are damaged in testing or if something were to occur, additional boards have been prepared for emergency swaps.

As for the main board itself, it sits at 92.7 mm * 84.8 mm in size. Most of the board's non-RCL components are LEDs, which have a low electricity requirement - each of them need 2.1 volts and 20 milliamperes of current. Quantity is a quality all on its own, however, as there are thirty LEDs being powered. Additionally, there are the PIDs. These are slightly more power-intense, requiring 5 volts and 65 milliamperes of current running through each of them. In order to accommodate all of these pins, the board uses four shift registers and a multiplexer.

## V. Software

This section will cover the software of our project. The software can be split into two main parts. The embedded code and the machine learning algorithm.

### A. Software Concept

The embedded software for the project will be flashed onto our designed PCB using the C language. The microcontroller chip is the ESP32-S3-Wroom-1 (ESP32). This chip provides a numerous number of GPIO pins, I2C and SPI controllers. The I2C controller will be used to communicate with the Jetson Nano. This part of the software will control most of the peripherals found in the device. For example, the LEDs, LCD display, fans, and IR sensors are all controlled by the ESP32 chip. Each of these components will be wired to the PCB and receive input once the switch is turned on or the button is pressed.

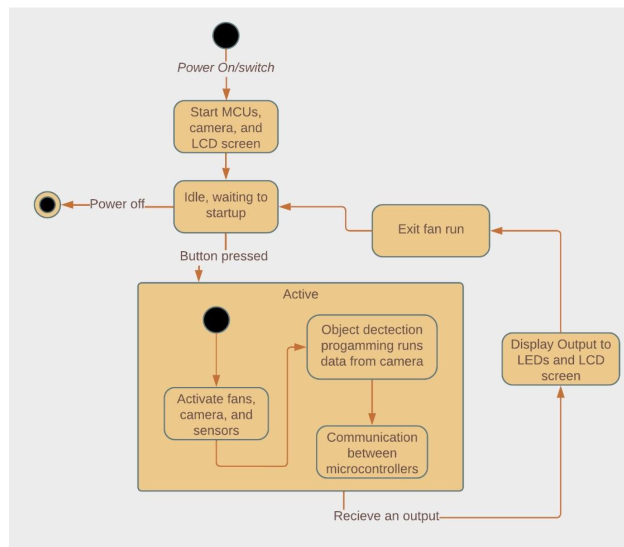


Fig. 6. Complete state diagram that shows the state of the device at any given point.

This state diagram helps portray the events of the system at certain points in the process. Once the device is powered on, most of the periheals will receive power and await a command from the ESP32 chip or Jetson Nano. The peripherals that will turn on are both microcontrollers, the camera, and the LCD display.

At this point, the system will remain idle until the button is pressed. This will put the device into the active state and continue the process of the device. In the active state, the object detection and IR motion sensor systems will monitor the bees and provide results. These results will then be fed to the leds and LCD to output for user interpretation. At this point the exit fan will begin to help navigate air out of the device to prepare for the next process. It is at this point that the device is back in the idle state and will remain in the idle state until the button is pressed again or the device is powered off via the switch.

As stated, the ESP32 will be in charge of the visual output representation. The two visual outputs will be the LEDs and LCD. Each visual output will portray both the IR sensor system and optical system, five outcomes for each system.

To explain further, based on the results found the LEDs will light up green or red. Green for a successful result, when the bee proboscis is detected, and red for an unsuccessful result. The LCD will output the same results on a display. A grid two by five grid will be provided and labeled based on the system. Each row will represent one of the systems and each column will represent one of the five bees. Under the grid will be other statistics such as response time and accuracy. Below is the flowchart to further demonstrate the visual output representation.

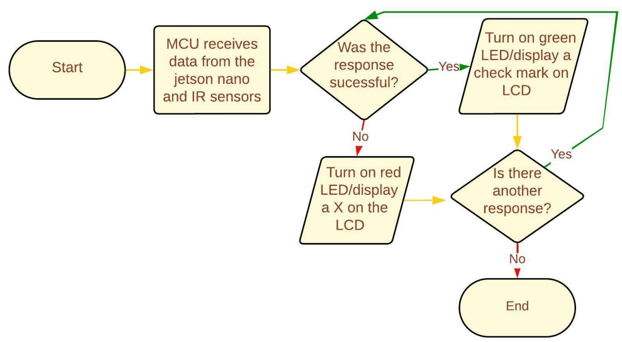


Fig. 7. LED/LCD flowchart.

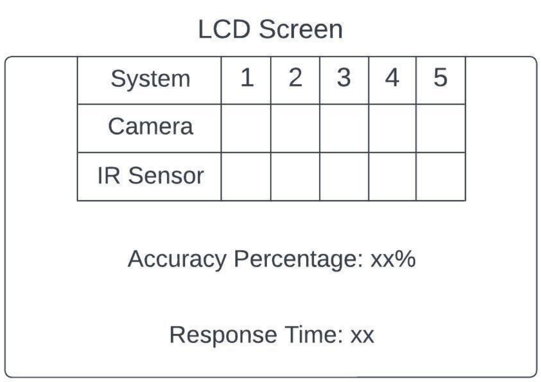


Fig. 8. LCD Interface

*B. Machine Learning*

For detection of the bee proboscis we opted with object detection and to utilize the YOLOv4 model. This particular model is a two-stage detector that extracts a region of objects in the first stage. The second stage will further cleanse the localization of the object and help with detection. This model utilizes CSPDarknet53–which is a neural network utilized with deep learning algorithms–which is the backbone for the YOLOv4 model. YOLOv4 also utilizes DenseNet which connects the layers of Darknet. To understand what the model does, a simplified description of Darknet–it consists of layers that include an input layer, one or more hidden layers, and an output layer.

Following the backbone is the neck which is PANet–which aggregates the parameters that are developed from the different layers of the backbone and can then be passed forward to the top layers that apply classification. Adaptive feature pooling then creates cleaner connections which fuses the information from both ends together from the different layers.

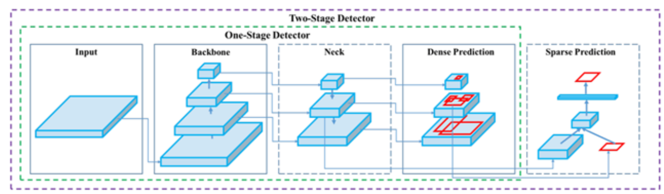


Fig. 9. Structure of the YOLOv4 model. *[4]*

With the model picked and the breakdown of it–next is how implementation is done within our system. The model first needed to be trained for our purposes. This required a custom dataset. In order to ensure a properly trained model a large number of images were needed to allow for proper detection of the bee proboscis. To achieve this, images for bee proboscis were taken from available images online as well as images that we've taken from what our lens and camera sees as well to ensure that all bases were covered for the model. More images also ensures a more accurate model–this was done by utilizing a "Bag of Freebies" which is the process of editing images by flipping, rotating, and changes to brightness, contrast, and exposure. The dataset consists of over 200 images and was then passed to the object detection model for training. To ensure proper training, the dataset was split into what's considered the training images and validation images.

To make sure that the model has enough images to validate the training, 80% of the images were used for training, while 20% were for validation–this is a common split when training models. Following this the model was trained with different batch sizes of 16, 32, and 64 with the batch size of 64 providing the best results. Training was done across 6000 iterations, though this leads to over training on later weights, early weight files were saved after each 1000 iterations. For our system the weights file that provided the best accuracy while avoiding the issues of over training was the file generated at the 3000th iteration.

Training of the model was done through Google Colab to allow fast training of the model. Once training was complete, the weights file, configuration (cfg), and the file that classifies the names for detection were transferred to the Jetson Nano. The cfg file determines the number of convolutional layers, max pooling layers, and the routing methods used–mentioned earlier with the neck. This is also where modifications were done for batch size of the model.

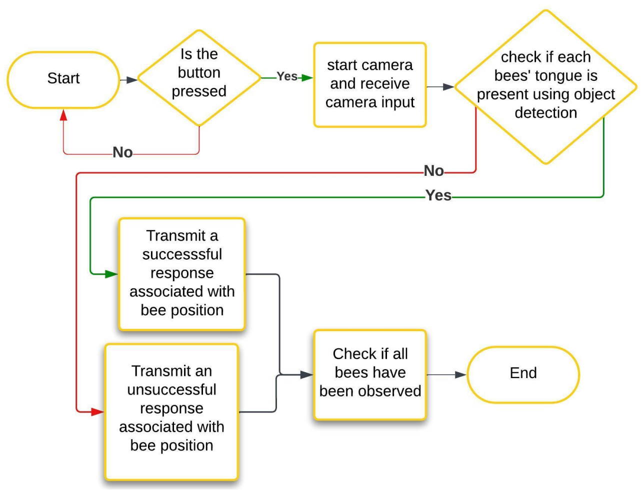


Fig. 10. Object detection flowchart.

The system that operates the model is done through Python and utilizes the libraries such as smbus and opencv to incorporate the I2C connection and the YOLOv4 model that will be run once the system detects the button input. To do this the python script will run on boot of the Jetson Nano–done by modifying the boot scripts on the Jetson Nano and will poll for the button press. For the I2C connection from the Jetson Nano's end, two functions (1) readNumber() and (2) writeNumber() are utilized.

(1) def readNumber() reads the connection that occurs over the I2C connection between the Jetson Nano and the PCB. The address of the I2C connection is read in by the read_byte_data function from the smbus library.
(2) def writeNumber() writes back data across the I2C connection to the PCB. The data that is sent back will be an array of simple ones or zeros depending on the check done within the python code.

Once a button press occurs and is detected from the PCBs side, an integer value of one is passed to the Jetson Nano as acknowledgement of the button press. Once it's read, the code then executes the object detection model for detection of the bee proboscis. This detection process will last sixty seconds. This is to ensure that a large enough window occurs for detection of the bee proboscis. Since the board is still a lower end board, the frames per second of the video is limited. This window will also allow for the device to operate and return results all within a minute allowing for a quick and consistent response back to the user.

While the detection runs, another check will be conducted. As the model detects objects, a score value will be generated and checked. It will begin by storing all the scores the model generates as it executes. After the model finishes running, the scores that are stored will be passed to another function. The function is called def checkNumber() and will take the list as its parameter. It will then conduct a check of the scores by comparing them to a confidence threshold of 0.7. This is to ensure a high level of accuracy from the system and that the model has detected a proboscis with high certainty. Once the check is complete the results will be passed back across the I2C connection with (2).

### *C. Communication*

An important part of the software came with the communication. Both microcontrollers must communicate with one another to transmit data. For example, the Jetson Nano will contain the object detection to find the results for the optical system. These results must be communicated with the ESP32 to display on the user interface. This data transfer can not be done with just one wire.

During our research, we found many options for communication between microcontrollers and decided to go with the inter-integrated circuit communication protocol. This is done with two wires. Each microcontroller will be connected to one another via the serial data line (SDA) and a serial clock line (SCL). The I2C pins for the Jetson Nano are pins twenty-eight for the SCL and pin twenty-seven for the SDA. [5] On the ESP32 the SDA pin is eight and the SCL is directed to pin nine. [6] Using I2C helps decrease the amount of connections needed and provides quick communication for a short connection.

I2C supports multiple masters, which is what we wanted to try to implement into our project. This became a problem after we had to change the communication protocol for the camera and Jetson Nano. To start, we wanted to use universal serial bus protocol for the communication. However we found that to be ineffective and switched to a MIPI CSI-2 wire which uses I2C communication. This created an environment of two masters, the Jetson Nano and the ESP32, and both masters could not communicate at the same time. This would decrease the overall response time of the device. The solution was to switch the ESP32 to a slave from a master. In the end this works well because now we can utilize the faster clock found on the Jetson Nano.

As stated before, the Jetson Nano uses another I2C communication, besides the communication between the microcontrollers. This communication occurs between the Jetson Nano and the camera. The Jetson Nano has two MIPI CS-2 connections on the board and one of these connections will be used to communicate with the camera. A MIPI CS-2 connector is a 15 pin connector used with many cameras. There are three ways this connection is made with the Jetson Nano. Either using a conversion board, on-board connection, or an expansion board. We utilized a conversion board for our connection. This will allow for the camera to properly communicate with the Jetson Nano via the I2C protocol.

## VI. Fabrication and Assembly

The device we will be constructing should be as lightweight as possible and able to be carried easily in the user's hands. This device will be constructed using a 3D printer. The 3D printing for this project will not be done in one go because this would take too long. Our design for the housing can be examined in parts.

### *A. Bee Tray and Harness*

The harness wearing bees will be safely housed inside of the device on a tray that will be locked in place. Each tray will be placed inside one of the two main chambers found within the device. The tray will hold the bees in place as the system's process is taking place. The location of the bees is optimized for both optical and IR systems. Below is an image of the tray that will be 3D printed to hold the bees.

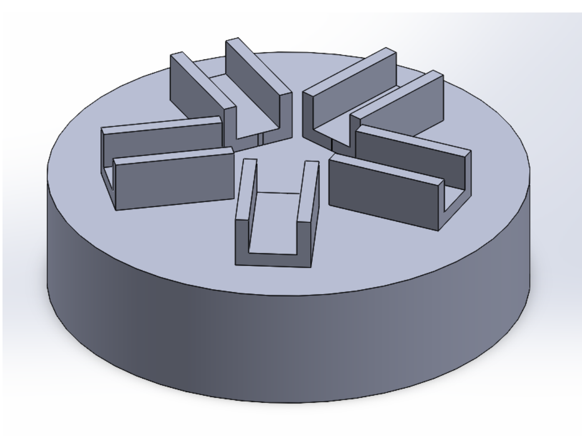

Fig. 11. Image and design of the tray.

## VII. Conclusion

To conclude, this project will use two primary systems - an optical system and an infrared system - to observe and detect the proboscis of bees, all in order to determine if there are any harmful substances. Through our research, we have found the best way to implement our design and achieve the desired results we wish to obtain.

## Members


Cole Correa is currently a senior student at the University of Central Florida seeking a degree in Computer Engineering. After graduation Cole hopes to pursue a job in software engineering.

Hussein A. Shelleh is currently a senior student at the University of Central Florida. He's seeking two degrees; one in Electrical Engineering, and another in Photonic Science and Engineering. Once he graduates, Hussein would like to spend time visiting family overseas.

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Trevor Van Baulen is currently a senior student at the University of Central Florida seeking a degree in Computer Engineering. Following graduation he seeks a career in AI and dataset automation with companies like AMD or NVIDIA.


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