



Bird Initiated Rubbish Disposal System

Healing the World Through Bird Power

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1. Executive Summary

[summary of paper]

2. Project Description

2.1 Motivation

For decades, governments and societies around the world have attempted to discourage the act of littering. Some have implemented educational programs to educate the public and others enforce it by law and threat of force. In the United States, public programs to incentivize proper waste disposal have mostly worked, at least for younger generations. However, a non-negligible amount of trash is still generated in public spaces, whether due to inconvenience or neglect.

All current solutions for public clean up involve extensive energy cost. Whether using volunteers, convict labor, or salaried street cleaners, they all require active effort to keep streets clean.

The most optimum solution for this issue is to ensure that people themselves stop littering, either by increasing accessibility to and educating the public about proper waste disposal or incentivizing products to be reusable and non-disposable. In the absence of that, we believe that harnessing the omnipresence of birds would be beneficial for the health of our public spaces.

The BIRDS project will be a device that can be used to train birds to pick up trash. Birds are very smart creatures and there have been many occasions where they have been trained with enough consistency. Since birds have such free access to many locations, they would be great candidates for picking up different bits of trash. The birds will bring in trash and be rewarded as long as they bring the right things in. This is a classical conditioning for birds to show them that depositing trash to the BIRDS is beneficial for them.

This will be a great project to take on as this could very heavily benefit areas that are littered with trash around the world. Along with trash pickup there are many different fields of expertise that can come together in this project. This makes it the perfect opportunity to learn more about our respective fields of Photonics Science and Engineering, Electrical Engineering, and Computer Engineering. This also helps us learn to learn more about finding the experts and getting help from all different fields to come together.

2.2 Introduction

This project consists of designing and building a device that will reward avian creatures to collect small sized trash from the environment around them into a temporary storage container for humans to collect and properly dispose of.

Using the theories on operant conditioning, we will design a bird feeder that will attempt to train birds to collect and submit trash in the housing for later collection. Operant conditioning refers to a psychological theory that proposes that behaviors can be learned through the use of and association with stimuli that either reinforce or discourage behavior. In our project we plan to use positive stimuli, such as food, to incentivize birds to repeat the behavior of submitting valid trash items into a designated terminal. In a sense, we are simply building a skinner box that rewards trash disposal for birds.

The birds will interact with the BIRDS through two terminals. One allows them to deposit items into the analysis chamber and the another will deliver a food pellet as a positive reward to associate trash in the BIRDS with food in the birds.

This project was originally proposed by our sponsor Justin Phelps. He saw a video of someone building a bird feeder that trained crows to collect and deposit coins into it. We of course have been influenced by similar projects, but to our knowledge, no one has tried to commercialize or mass produce such bird feeders.

2.3 Goals

2.3.1 Core Goals

Our main goal is to promptly feed birds that bring trash. For a conditioning machine to have a chance at training birds, the most critical element is quick and decisive activation of the reinforcing stimuli. The BIRDS must be able to respond to a trash submission within a short period of time in order for the bird to associate the action of submitting trash with receiving food.

Another critical goal is for consistent bird and trash detection verdicts. Other animals, such as squirrels, must not be able to interact with the BIRDS; otherwise, any chance of birds reaching the unit would be slim. Similarly, it would be disastrous for bird conditioning for a valid trash item to not be rewarded or the opposite of a non-valid object being rewarded. Such cases could ruin the conditioning or form unanticipated behaviors.

Since the BIRDS is meant to be placed outside in public spaces, the BIRDS should be as weatherproof as possible. To the bare minimum, it should be able to survive rain and humid conditions. The most critical sections for weatherproofing are the food storage, so the food does not spoil, and the internal circuitry and mechanical actuators.

2.3.2 Advanced Goals

With the core goal of timely and consistent delivery of food secured, adding supplementary stimuli when the food is dispensed should help associate the BIRDS with food, which in turn, associates food with trash delivery. Auditory and optical stimuli could easily be added to the system, such as bells or LED lights. However, the vibrations from the mechanical trash sorter and food dispenser should provide enough complementary stimuli.

For further reliability, the BIRDS should be rated for extreme weather such as hurricanes and flooding. We do not expect the systems to operate during such conditions, but it should be able to withstand adverse weather.

Since the BIRDS is meant to operate outside for long stretches of time, the BIRDS would benefit from being able to autonomously service birds for around a week. This would involve a power supply that is able to power all systems with a moderate amount of service for a week. Applying solar cells could alleviate the power demand during the day. And the last aspect for autonomous operation is that the storage units are large enough to hold a moderate amount of trash and enough food for such volume accepted.

2.3.3 Stretch Goals

Since training the image recognition software is challenging enough, we believe that for testing the performance of this project, the BIRDS will be trained only to detect cigarette buds for their simple shape and consistency.

The Stretch Goal then is to design the BIRDS to accept and detect multiple types of trash. That maybe pieces of plastic, bottle caps, plastic wrappers, etc. However, opening up to such a broad selection of items may prove challenging because of the different optical properties, not to mention increasing the chance for birds to submit something that may get stuck inside the housing or analysis chamber.

Another stretch goal is to be able to classify what kind of bird is in front of the housing. This seems like a task that might be too big to accomplish. Since we are developing on a smaller embedded device and not a big desktop system, classifying something like this might take too much processing power. It would be a nice addition if when saving images, we could say what kind of bird was being trained.

As with any ordinary bird feeder, aesthetics matter. If we have time, it would be nice to design the housing and external components to look visually appealing.

2.4 Objectives

In order to implement rapid, selective service to birds, we need a way to detect whether a bird is ready to interact with the terminals of the device. A mechanical and electrical system will unlock access for the bird to interact with the terminals and prevent any other animal from accessing the terminals. The bird then would deposit a trash item into the drop chute for the analysis chamber. Then the BIRDS determines whether it's approved or not and reacts accordingly. It releases food if the item was approved, and a stimulus would play if it an item was detected but not approved.

2.4.1 Housing

The BIRDS will be designed as a structure that keeps the inner compartments safe from the weather. There will be enough volume within the structure to store food and trash compartments.

The birds will interact with the device via two terminals. One terminal allows the bird to drop items into a trash analysis chamber to validate whether it is a valid trash item. The other terminal allows food pellets to drop from a storage container to reward the bird upon successful submission of valid pieces of trash. However, the BIRDS will need a way to discard not disapproved items separate from the approved storage.

The BIRDS will have at least two storage containers for the accepted trash and food storage respectively. The BIRDS is being designed for weekly maintenance for trash removal, food replenishments, and battery life without recharging.

2.4.2 Sensing

The device will make use of an optically designed sensor to detect and exclusively service birds, another optical sensor to validate whether the submitted item is an acceptable object, and a simple motion sensor to wake the BIRDS from a power efficient sleep mode.

To give timely and consistent responses for the birds, we need to design sensor systems for image processing of trash and birds in the trash analysis chamber and outside the terminals respectively.

The bird sensor should be weatherproof, low light or night vision, and disregard natural noise such as rain, fog, shadows, etc. There should be a more rudimentary motion sensor that enables the more energy intensive image recognition sensor to save power. The trash analysis sensor should be able to view the entirety of the chamber and be calibrated for the mostly constant image conditions inside the device.

Preferably both sensors will consume as little power as possible, but if not, the low energy motion sensor to wake the device should prove sufficient enough to save power.

2.4.3 Identification

As a natural extension of the previous objective, the BIRDS will need an image recognition software that can approve or disapprove a submitted item. The software being used will be trained models on their respective systems for birds and for trash. These models will be run on a separate machine learning system that we will go into more detail later on. In order to achieve our goal of accurate training of birds we must make sure that we minimize a false negative occurrence.

2.4.3.1 Confusion Matrix

In any sort of statistics-based approach there is an important aspect that goes into the prediction that is not just the probability of guessing right. There is something called a confusion table or sometimes referred to as a confusion matrix. This is a table that can show extra details about how the data is being picked accurately or inaccurately. In machine learning this is used the same exact way.

A confusion matrix using a binary classification such as ours is a 2 by 2 table that consists of the rows being the actual condition or the label, and the columns being the predicted condition or the prediction. When filled in properly this makes a confusion matrix with the 4 squares inside being labeled as follows, true positive, false negative, false positive, and finally true negative. Let us take the example of our bird classifier, a true positive is when both the label and the prediction match the expected value of both being the same and both being saying that a bird is front of our system. A false negative is where the actual classification a positive value, but the predicted value was negative, so there was a bird in front of the system, but the classifier said that it was not a bird. A false positive where the actual classification is false, but the predicted value was true, so there was not a bird in front of our system and the classifier thinks there was. The final one being a true negative where both the actual classification and the predicted classification agree that both are negative, so this is when there is not a bird in front of our system and the classifier also agrees that there is no bird in front of our system.

2.4.3.2 Final Confusion Matrix Choices

With both of our systems it is important that we do our best to minimize one of these outcomes while trying to maximize the correct responses. For the bird system it would be best to minimize a false positive. Our reasoning for this is that the most common animal to try to take down bird houses are squirrels. Because of squirrels always being destructive to bird houses, we must limit the access of squirrels at all costs. With our housing being tamper proof and our image classifier minimizing the chance of guessing a bird when a squirrel is in front of our housing, this will limit the destructive nature that the squirrels always tend to have in bird feeders.

In the trash system minimizing one particular part of the matrix becomes a bit more challenging. The question to ask is to either be okay with rewarding birds for bringing something that is not

trash like a stick, or to be okay with not rewarding birds when they bring trash. Both of these options would have a negative effect on training of the birds. With the first option, there might be times where the bird associates stick with the correct object to bring. This means that the bird just associated bring a stick, which is everywhere for birds, with being rewarded with food. This leads to the bird learning that sticks give you food which is not the intention. On the other hand, the opposite option begins to not reward birds with proper objects being brought. This leads to birds associating trash with nothing at all. This will cause birds to not want to go out their way to bring anything to our system. In the beginning it felt hard to select which option was best for our means of training. After giving it more thought we concluded that rewarding negative behavior, the bird bringing a stick, would be worse than not rewarding positive behavior. This is similar to how training any animal works that you never want to reward negative behavior if you want it to stop. This makes our final option to minimize the false positive where the bird brings something that isn't trash and gets rewarded for it.

2.4.4 Actuators

To get objects to where they are designed to go, we need to design mechanical and electrical systems to dispense a certain amount of food and to collect or disregard submitted items from the trash analysis chamber. Preferably simple mechanical systems to avoid wear, maintenance, and to function in most weather conditions.

And lastly, a mechanical and electrical system to close and open the terminals for use. Such doors should be designed to optimize weather proofness.

2.4.5 Power

For the BIRDS to operate autonomously for weeks, we need to design a power system that will supply all the subsystems on battery alone for at least a week. And to integrate a solar array for continuous charging of the battery.

As much as we would love a totally independent power source, the BIRDS will need charging ports and access to power functions from the outside.

In order to achieve long-lasting independent operation, the BIRDS will initiate a sleep mode when not in use. Then, through the use of low power motion sensors, the BIRDS will awake for higher level processing.

2.4.6 Embedded Processing

We will design the control and processing units to coordinate and operate all the subsystems. The BIRDS will be designed for ease of maintenance and should include a battery charge indicator, activity log, and perhaps a recorded image log. For further ease of use, the BIRDS should have externally accessible data ports to interphase with the processor for activity logs or error messages.

Along with battery charge indicators, there should be some indicator for food running low and trash being full. This could easily be accomplished with a transparent section on the storage units or with a more complex electrical sensor and display.

To be able to handle the heavy computational cost of image recognition software, the BIRDS will operate using two sets of processors. One energy efficient central processor that will manage and control all subsystems and a higher power processor for the image recognition.

2.4.7 System Block Diagrams

Figure 2.4.7.1. Hardware Flow Diagram

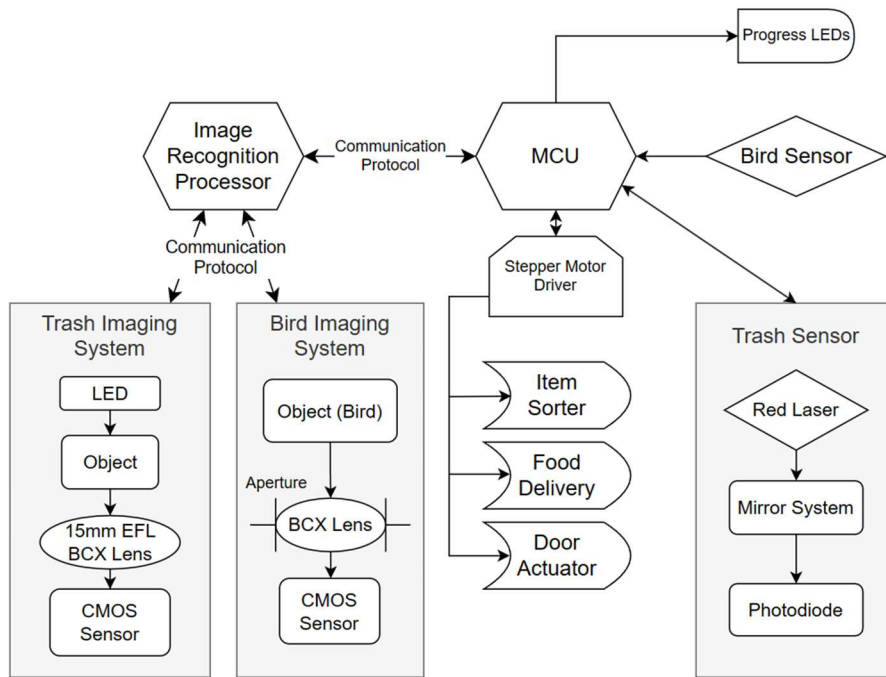
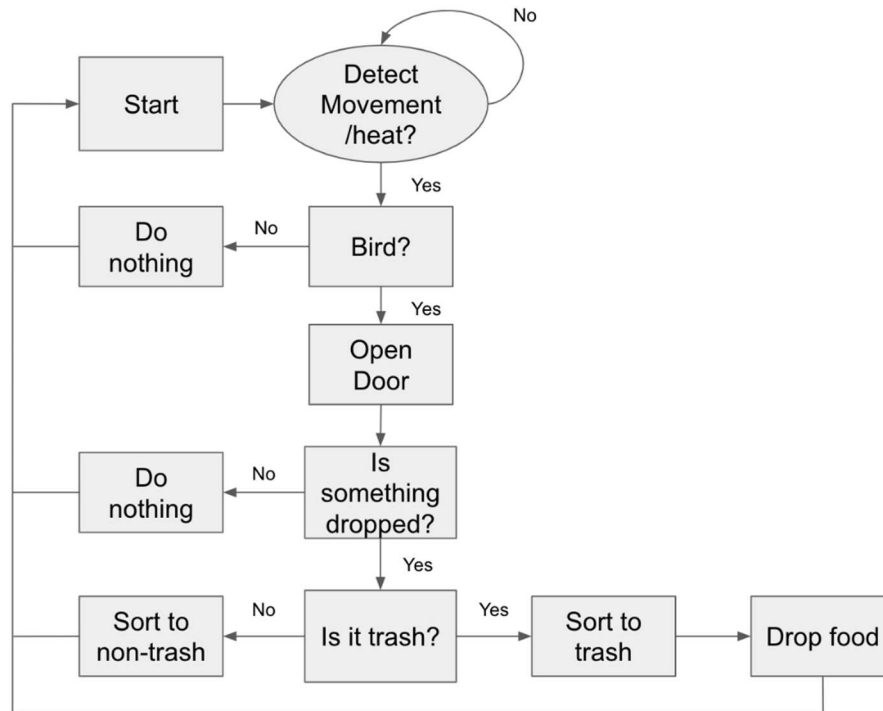


Figure 2.4.7.2. Software Flow Diagram



2.5 Required Components

2.5.1 General Summary

The primary consumer of the BIRDS is intended to be local governments, large universities, and environmental companies in a densely populated area. To meet the needs of the consumer, part specifications are given. The overall housing unit is still in the design phase; however, the electrical and optical hardware constraints are shown.

Table 2.5.1.1. Component Specifications

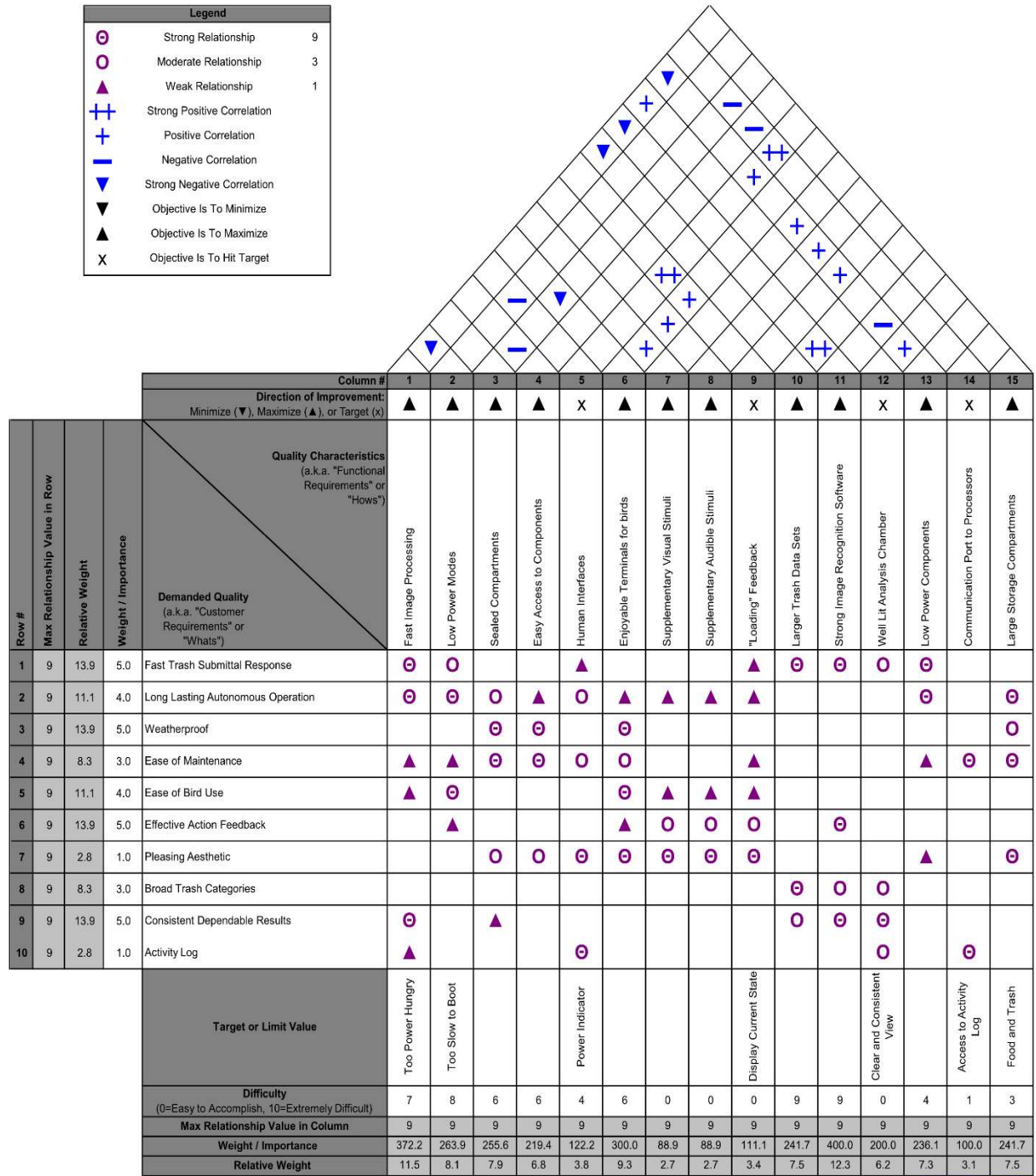
| Type | Component | Parameter | Specification |
|------------|---------------------------|-------------------------|---|
| Electrical | Power Supply | Charge Density | Power all functions for a week |
| | PCB | Central Control | Low power draw |
| | Solar Cell | Charge Amount | Enough to charge the sleep draw |
| | Motors | Reliability | Operate without fail 95% of the time |
| | Image Processor | Computational Power | Deliver a verdict within 2 seconds of taking the image. |
| | Status Displays | Human Interface | Simple, cheap, and weatherproof |
| Optical | Focusing Lens (Trash Cam) | Focal Length | 6mm |
| | Red Laser Module | Spot Size | 6mm @ 5m distance |
| | Photodiode | Wavelength Range | 400-1100nm |
| | CMOS Sensor (Trash Cam) | Resolution | 640 x 480 |
| | Mirror | Wavelength Range | 400-700nm |
| | CMOS Sensor (Bird Cam) | Sensor Size, Resolution | 640 x 480 |
| | Lens (Bird Cam) | Focal Length | ~5 mm or less |
| | Aperture (Bird Cam) | Aperture Size | f/2.8 or higher |
| | | | |
| | | | |
| | | | |

Table 2.5.1.2. System Specifications

| System | Parameter | Specification |
|-------------------------|-----------|---------------|
| Bird Image Recognition | Accuracy | |
| Trash Image Recognition | Accuracy | |
| Bird Motion Sensor | Accuracy | |
| Trash Motion Sensor | Accuracy | 80% |
| Main Door | Time | |
| Trash Separator | Time | |
| Food Dispenser | Time | |
| Solar Cells/Power | | |
| | | |

2.5.2 House of Quality Analysis

Figure 2.5.2.1. BIRDS House of Quality



3. Research

3.0 Existing Similar Products

One of the previous products that was foundational to our motivation behind the BIRDS is the Crow Box. Joshua Klein invented the Crow Box after an intensive study of corvid behavior. His idea was to create a housing unit that would entice crows to collect coins found in nature and bring them in exchange for food. The motivation behind the Crow Box was to work with synanthropic species, like crows, rather than continuing to live in frustration with them. Klein wanted to find a way to live mutualistically with crows. His end goals of the Crow Box are to eventually train crows to pick up trash after large events, find reusable components in discarded electronics, or even assist with search and rescue operations. Finding an equilibrium with crows and other synanthropic species may improve our lives more than we may think.

Another similar product to the BIRDS is a past Senior Design project at the University of Central Florida entitled the Smart Bird Feeder. This team of young engineers wanted to create a bird feeder that would deter squirrels and allow users to easily take care of the feeder. They utilized a computer vision machine learning model to identify between squirrels and birds as well as the species of birds. The students designed a user-friendly interface via a phone application for consumers to see what type of birds come across their feeder, and a notification system was designed to alert users when more food needed to be added to the Smart Bird Feeder. A unique feature included in this project that the BIRDS will also include is solar panels to provide power to the entire unit. Due to the desire for the BIRDS to be self-sufficient apart from food replenishing, solar panels will be implemented unlike common bird houses on the market.

These existing products provide a basis for how we will design our system. The Crow Box and Smart Bird Feeder each have their pros and cons that we hope to apply to the BIRDS. Knowing the downfalls in each will allow us to learn from these projects and build a structure that can train birds to pick up trash.

3.1 Bird Psychology

It is crucial for our team to research and understand the basics of bird psychology; otherwise, the BIRDS may become another post for birds to rest on without enjoying the full functionalities. However, it is important to note that this project seeks to achieve the core goal of designing and building an apparatus that will carry out all the necessary tasks should a bird bring trash to the unit. Our goal is not having birds fully trained with the BIRDS to bring trash in exchange for food. We hope that teams down the road will take on the task of assisting in training birds to use this system.

One key feature of birds is their intelligence compared to other animals, including primates. Some birds are especially known for their brilliant minds, like corvids and psittacines. They are considered among the most intelligent animals, and crows, specifically, have almost identical proportions of brain mass to body mass when compared with chimpanzees. (Klein, 2008)¹ The brains of parrots and songbirds contain on average twice as many neurons as primate brains of the same mass, indicating that avian brains have higher neuron packing densities than mammalian brains. Additionally, corvids and parrots have much higher proportions of brain neurons located

¹ Ted Talk – Joshua Klein

in the pallial telencephalon compared with primates or other mammals and birds.² Birds are beautiful creatures that we believe should be studied further to find more ways of mutually benefiting them and humans.

3.1.1 Feeding Behavior

Understanding their intelligence, we can easily see why birds exhibit remarkable problem-solving abilities related to obtaining food. They can navigate complex obstacles and puzzles to access food rewards, and some bird species exhibit tool usage in their foraging behaviors. For example, New Caledonian crows are one of only a handful of birds that forage with tools. They utilize hook-shaped sticks that they fashion from twigs to fish out grubs and other bugs from hard-to-reach places, like trees.³ Other birds have demonstrated this behavior in a closed environment.⁴

In some cases, birds learn about food sources and foraging techniques from other birds and species. This can involve observing the feeding habits of more experienced individuals and imitating their behavior. The reason this is important is due to the hypothesis, termed “behavioral drive”, about behavioral innovation and social transmission, referring to the non-genetic spreading of a new skill among a species.⁵ When animals show both frequent innovation and fast social learning, new behaviors can spread more rapidly through populations.⁶ On a university campus in Japan, Carrion crows have been observed dropping nuts in the road. While cars are stopped at a red light, the birds hop in the road and place walnuts in the middle of the street. After the lights turn green, the birds fly away and vehicles drive over the nuts, cracking them open. Finally, the crows fly back to the road when it is safe and eat their food. The crows have been observed doing this since the 1990s, and today, more and more crows have joined in on the walnut cracking.⁷ In a study done in 2007, random, wild pigeons were put to four different tests. Two of these tests involved innovation and social learning. The results showed a strong correlation between innovation and social learning as the majority of the birds that passed the innovative test also passed the social test. These researchers believe the co-occurrence of innovativeness and social learning is a pre-requisite for the potentially accelerating effect of cognition on evolutionary rate.⁶

As research is discovering more ways that birds are innovating and sharing behaviors, we hope this strengthens our goal of birds learning how to use the BIRDS very rapidly and efficiently in groups.

Another important factor in the feeding behavior of birds is what they like to eat. The type of food used in the BIRDS will attract different species of birds. Based on research shown above, corvids, psittacines, and columbidae have been found to be the more intelligent birds and are the specific families of birds we are looking to attract; however, the BIRDS will be designed to accommodate any birds that bring trash.

Food enjoyed by the corvid, psittacines, and columbidae are typically seeds, fruits and cracked corn. Specifically, corn is desired by larger birds, and it can be fed in small amounts, mixed with

² Olkowicz, 2016

³ Coleman, 2022

⁴ Rutz, 2016

⁵ Wyles, 1983

⁶ Bouchard, 2007

⁷ Davies

white proso millet, on platform feeders. However, with millet, this food can attract unwelcome species which is accounted for with our bird imaging system.⁸

3.1.2 Landing Pad Appeal

To attract birds to the BIRDS, we must design the housing so that it is suitable and enjoyable for birds to land on. An appealing and advantageous landing area for birds that gives them an optimal and comfortable experience will prove to be key in the progression of our goals and objectives for the BIRDS. In the Smart Bird Feeder Senior Design project, the landing area for birds was a rod positioned directly in front of the feeder, which made it natural and easy for birds to have something to grip onto when feeding. As another design example we referred to, the commercial Smart Bird Feeder made by Bird Buddy utilizes a brightly colored, visually appealing, and grippy landing pad for birds to land on when feeding. For our project, we anticipate designing an appealing and comfortable landing area for birds to come and both dispose of trash and feed from the bird feeder. Therefore, we decided that a platform positioned in front of the dispenser for birds to land on and have sufficient space seems to be the most natural and appealing design.

There are many different structures that make up the whole system of our bird feeder. Due to the many electronic and optical systems that need to be housed, we have chosen a typical house-like design that will act as a platform dispenser. Most of the physical structure will be housing and aesthetics, which are areas that will not be captured by the bird camera, and then the area where the action will be happening will be a platform attached to the front of the feeder. The bird imaging system will only image birds that land on this front platform of the structure, which will be the landing pad. To prevent birds from landing on other parts of their structures, some designers created products that utilize bird deterrents on their feeders in the form of physical structures on these specific parts of the feeder that they don't want the birds to get distracted by and land on. Spikes and sharp corners prevent the birds from landing on surfaces of the feeder that the designers don't want the birds landing on, like the roof of the house structure, for example. We will design a housing unit that does not have these obstacles out of a desire to encourage birds to land on the BIRDS and to promote safety for our avian friends.

3.2 Peripheral Devices

The BIRDS will make use of several components for Low-Power Mode optimization and to enact the required behaviors to accomplish our goals.

The BIRDS will need at least two low-power sensors: one to activate the bird detection camera and one to activate the trash detection camera. These cameras and their image detection software will most likely be the most energy intensive systems in the BIRDS. Therefore, we want to minimize their utilization as much as possible.

Once a bird is detected and verified, the BIRDS will need an actuator to at least open the trash submittal terminal. Then, when the trash is detected and verified, it will use an actuator to sort the trash item into their storage container and another to dispense food to the bird.

⁸ Willcox, 2019

3.2.1 Actuators

The moving parts of the BIRDS will make use of motors and actuators to open the trash submittal terminal, open the food delivery terminal, and rotate the trash sorter mechanism.

The following subsections will discuss all the available actuator technologies and discuss their compatibility with the BIRDS's goals.

3.2.1.1 DC Motor

“A DC (direct current) motor is an electric motor that converts electrical energy into mechanical motion. It operates on the principles of electromagnetic induction and the Lorentz force. The motor consists of an armature (a coil of wire), a stationary stator (containing magnets or field windings), and a commutator (a split ring attached to the armature).

When an electric current flows through the coil in the armature, it generates a magnetic field. This magnetic field interacts with the fixed stator magnetic field, resulting in the Lorentz force, which creates a torque, causing the armature to rotate. The commutator is responsible for reversing the direction of the current flow in the coil, ensuring continuous rotation of the motor.

There are various types of DC motors, including brushed and brushless varieties, which differ in commutation methods and efficiency. Brushed DC motors use physical brushes and a commutator, while brushless DC motors employ electronic control and sensors for commutation, offering improved efficiency and reliability.”⁹

To control the speed, you can implement a pulse width modulating signal into the input port, or you can get a dedicated DC motor driver board that controls its speed and rotational direction. There are a few variations of DC motors, the first is whether its brushed or brushless (brushed are generally cheaper but create more heat from friction, and therefore are less efficient; brushless can reach higher speeds and are more efficient, that being, more expensive), and the second is whether it provides rotary or linear motion.

For the BIRDS, we were considering DC motors to serve as a rotary actuator to drive the trash sorter and food dispenser. However, while being very simple to operate, the lack of fine positioning, precise torque application, and possible need for a dedicated driver board discourages us to utilize DC motors into the BIRDS.

3.2.1.2 Stepper Motor

One step higher in complexity, a stepper motor builds upon the simpler DC motor technology. A stepper motor uses direct current to induce a magnetic field that interacts with fixed magnetic fields in the body of the motor. Unlike DC motors, as described by its name, a stepper motor takes steps that jumps to discrete ridges in the fixed magnetic field, almost acting like magnetic gears.

“A stepper motor consists of two key components: the stator and the rotor. The stator comprises coils or windings, while the rotor is equipped with teeth or magnetic areas that interact with the stator's magnetic poles.

Stepper motors are categorized by the number of phases they possess, typically two or four. Each phase involves a coil that can be electrically energized in a particular sequence to induce rotation.

⁹ [GPT – Component Research – Ans 2] DC Motor Description by ChatGPT

To initiate movement, a specific phase is energized, and the magnetic field generated by that phase draws the rotor's teeth or magnetic regions towards it. These motors operate in discrete steps, with common sequences being "full step" and "half step." In full-step mode, each phase is energized sequentially, while in half-step mode, two phases can be energized simultaneously at varying levels to achieve smaller steps.”¹⁰

These fixed steps allow for great control on positioning and torque. However, this technique requires a lot more complexity to operate than a simple DC motor. Stepper motors also operate with pulse width modulation signals, but since there are multiple phases to coordinate for one rotation, stepper motors need dedicated driver boards to operate. This complexity requires Stepper Motors to operate with a dedicated Stepper Driver board. This driver board requires several controller pins, 4 pins for the motor we were looking at, and a dedicated power source. We are interested in this technology for the precise control of rotation for possible application on the trash sorter and food dispenser. However, the increased complexity of operation and the need for at least 4 pins to control still remains a possible option, but would prefer for a simpler motor.

3.2.1.3 Servo Motor

Even more complex than stepper motors, servos work by a combination of sensors and actuators to achieve a desired position.

“The servo motor's precision arises from its closed-loop control system. This system employs the position feedback device to continually monitor the motor's current shaft position. This real-time feedback ensures that the motor is always aware of its exact position.

To guide the servo motor's movement, a target position, also known as the setpoint, is specified. The control circuit calculates the error, which represents the variance between the desired position and the motor's actual position.

A control signal, often in the form of a pulse-width-modulated (PWM) signal, is computed by the control circuit based on the error calculation. This signal regulates the voltage or current supplied to the motor, influencing its movement.

The motor responds to the control signal and initiates motion, adjusting itself until the feedback system confirms alignment with the desired position.

The servo motor continually fine-tunes its position by assessing the feedback against the target position, enabling it to respond quickly to any deviations. This adaptability makes servo motors well-suited for applications demanding precise and real-time control.

In addition to position control, servo motors also manage speed and acceleration. By modulating the control signal, they deliver smooth and controlled motion profiles. Furthermore, servo motors offer substantial torque output, even at low speeds, catering to applications that require both accuracy and strength.”¹¹

As a closed-loop control system, a servo motor uses sensors to provide feedback to its control system about its current position. Based on its feedback, a servo utilizes its actuator, that can be a DC or AC motor, to drive its position to a desired state. While having the most complex motor

¹⁰ [GPT – Component Research – Ans 4] Stepper Description by ChatGPT

¹¹ [GPT – Component Research – Ans 6] Servo description by ChatGPT

system, since it already includes its feedback and control system, servo motors have very simple interface. Servos usually only need one control pin and dedicated power supply. They are controlled by pulse width modulation to control speed and direction. For the BIRDS, this versatile motor could be implemented for trash analysis chamber and terminal door system. However, because of the nature of a closed-loop system, a servo motor has to constantly check and confirm its position, this means that even if it is not in use, it continues to draw current. This could be detrimental to the goal of energy efficiency, but we could simply divert power away from them until they are needed, but that adds complexity to the power circuit.

3.2.1.4 Solenoid Actuator

Probably the simplest actuator technology, a solenoid actuator has two states, extended and retracted. By running a current across a coil, it forms a magnetic field that then attracts or repels from a fixed magnetic core creating linear motion along an axis. This could be an interesting option for driving a rudimentary extending door. While simple, the extent of the linear motion varies, but most are very limited as to a few centimeters. This limited range, in addition with the substantial draw to maintain the piston activated for long periods of time makes the solenoid actuator an unsuitable choice for the BIRDS.

3.2.2 Light Emitters

Preferably, the BIRDS will use light emitters to supply additional stimulus for bird training and association. We believe that some type of display that illustrates the current stage of the BIRDS would be beneficial for the birds and for us to debug. In addition to display elements, the BIRDS will need a light emitting device to illuminate the trash analysis chamber for the camera to take a clear picture of any introduced item.

3.2.2.1 LEDs

The easiest, most versatile, and cheapest in cost and power is the light emitting diode. We are most likely going to depend on LEDs for all illumination needs. Light emitting diodes work because of a specific PN semiconductor boundary configuration. By applying voltage across an LED, electrons are forced to move across that semiconductor boundary layer that because of electrons passing through, they go from a high energy state and release light of a specific wavelength as they cross the boundary layers. LEDs are by far the most energy efficient light emitting device out there.

For the current-stage display, we can have an LED light up for each new stage progressed.

3.2.2.2 Incandescent Bulb

The oldest and least efficient light emitter. Incandescent light bulbs run current through a special filament, that essentially works as a resistor, that is specially designed to emit as much visible light when heated to a certain temperature. Because of specific conditions are required for the filament to work, incandescent bulbs require... bulbs. These bulbs serve to keep the filament in a vacuum as for it to not ignite with oxygen. This vacuum requirement makes bulbs limited in how small they can physically be. Since much of the energy is wasted in heating the filament and emits heat and useless wavelengths, the incandescent bulb is not a very energy efficient device, and therefore, does not comply with our energy efficiency goal.

3.2.2.3 Fluorescent Bulb

Similar to Incandescent Bulbs, fluorescent bulbs emit visible light when a voltage is applied to it. However, instead of running current through a filament, fluorescent bulbs emit light by ionizing a gas contained in the bulb. This makes fluorescent bulbs more efficient to incandescent because there is not as much wasted heat energy. But fluorescent bulbs are more constrained in shape and size, as well as the need for large voltage difference for ionization. These constraints are hard to reconcile with our energy and size constraints.

3.2.3 Acoustic Emitters

If we wanted to implement additional auditory stimulation, the BIRDS will need some type of audio component. We are thinking of adding auditive stimulation when the capacitor sensor wakes the BIRDS, another when a trash item was validated, and another when food is dispensed. It would be useful if we implemented a fail or invalid item stimulus as well.

3.2.3.1 Buzzer

A simple oscillating object that can vibrate at a certain frequency. Some allows for selected and changing frequency. Such buzzer would allow us to utilize only one buzzer for all the possible tones we could need.

3.2.3.2 Bell

Bells are simple metal objects in a shape that creates a distinct sound when struck with another metal object. The only reason why we even consider this is because of the historical usage of bells in skinner's conditioning experiments and because they are fun to listen to.

In order to implement a bell into an autonomous system, we would also have to add some type of actuator to ring the bell. Current commercial bell controllers are quite expensive, and building our own would be too much trouble for something so frivolous.

3.2.3.3 Speakers

Speakers work by oscillating a membrane, usually with magnetic pulses, to certain wave signals. They are the most widely used audio system because of their versatility in producing an immense variety of sounds. However, this versatility is due to sound drivers and dedicated sound boards to drive the speakers by converting digital signals into analog, then amplifying them to drive a speaker. This is way too complex for a simple auditory stimulator and therefore out of scope.

3.2.4 Human Interface

In the same spirit of providing supplementary stimuli for the birds, it would be useful to implement some type of human interface for maintenance and debugging purposes. We think that at the very least, the BIRDS should have a battery charge indicator. Other human interface features may be added in future design decisions.

3.2.4.1 Battery Charge Indicator

For a battery charge indicator, we could use any type of display from OLED, LCD, or simply add a row of LEDs.

OLEDs, or organic light emitting diodes, are too expensive and require drivers and communication ports to operate. They are too complex for a simple battery indicator. This is the same case with an LCD screen, so neither are good options.

Most likely, if we implement a charge indicator, it would be a row of 4 cheap LEDs that represent the charge of the system. This design would be simple enough to not consume much power yet sufficient enough for users to maintain power for their BIRDS system and know when it needs to charge.

3.2.5 Motion Sensors

Another set of peripheral devices needed for our design is the sensors that will be used to communicate with the central control unit on when to turn on the bird and trash camera systems. The cameras within our system will resort to a sleep mode in which power is conserved, and the sensors will serve as the means by which the cameras will be turned on for imaging. These sensors will need to be fast enough to provide minimal delay between detecting the bird and rewarding the bird. They will also need to be cheap and operate at a low power so that their use is worth the time and cost of implementation.

First, there will be a sensor for activating the bird camera system. The sensor for activating this imaging system will need to operate quickly enough for the controller to be notified, activate the camera, and take a picture, ideally of the bird on the landing pad. It will need to operate at a low power that makes its addition to the system and assistance in lowering overall power consumption worth the extra cost and commitment. Options including a motion sensor and a touch sensor were considered and are outlined in the following sections. In addition to a sensor for bird imaging, a sensor for activating the camera for the trash imaging system will be needed to conserve the power consumed by the camera of the trash subsystem running. This sensor will need to operate quick enough to minimize the time it takes for food to be dispensed to reward the bird before it leaves. Decreasing this time delay will be a crucial part of our system's design. Research of the optical and electronic capabilities of various options for bird and trash sensing was done, and the following sections outline the options we considered in our project development and design of the sensors for our optical subsystems. Research and development of the optical subsystems controlled by these sensors is detailed in 3.4.

3.2.5.1 Infrared Motion Sensor

Knowing that power consumption would be too high if the external camera system for bird detection was always running, we anticipated the need for a low-power activation system for the camera. This section outlines the thought process and research conducted on the possibility for a passive motion sensor to be implemented so that problems with battery consumption could be minimized.

The idea was to have a motion sensor, placed at a similar vantage point to the camera, that would activate the camera upon sensing a movement in the proximity of the landing pad. The idea was to use a passive infrared (PIR) motion sensor, typically used to detect human body heat signatures, and tune it to detect the unique heat signatures of birds. Another idea was to use an ultrasonic sensor, serving the same purpose as the motion sensor of activating the imaging upon detection of movement near the landing pad. The sensors would be adjusted to specifically detect the area surrounding and including the landing pad for the birds, in attempt to isolate birds in our detection.

A PIR motion sensor has two slots that are sensitive to IR radiation, and when a warm body like a human, or a bird in our case, passes between the two sensing paths from each slot, a differential is detected upon the body leaving one of the paths. Like the creators of the Smart Bird Feeder mentioned in their motion sensor selection and comparison for their senior design project in 2021, using a simple line-of-sight laser sensor with a photodiode would create too much sensitivity and, therefore, too many false positives for our system. Since the laser trips when obstructed or when it is moved itself in any way, we would run the risk of the camera activating for too many movement detections that aren't birds. Even movement of the system itself because of wind or another animal interacting with the system would cause the sensor to trip. Therefore, this laser sensor system will be exclusive to just the trash chamber, detailed in 3.2.5.3, because the trash chamber will be less prone to unwanted activations from movement. The trash laser sensor will be fixed to the trash chamber it will be imaging, and so it will not run much of a risk of false positive activations from the entire system moving around. Using an external laser sensor, on the other hand, would make the activation system very prone to movements in its field of view of the immediate environment.

When researching applicable motion sensors, we struggled finding a solution capable of isolating only birds before turning on the camera for image recognition. Because of factors including sensitivity, accuracy, and feasibility, we scrapped the motion sensor for a capacitive touch sensor built into the landing pad of the feeder. This alternative camera activation is detailed in the following section.

3.2.5.2 Capacitive Motion Sensor

The magic behind the technology that is utilized today in touch screens and sensors is the capacitive sensor. Capacitive sensors work by charging and reading the length of time it takes to discharge the energy stored in the parasitic capacitance when something that can retain charge touches the reading node. This node can be extended as long as desired, therefore making it a great option for a sensing pad for our bird detection system. For the BIRDS, we will utilize a large, one-bit, capacitive sensor to detect if something has landed on the landing pad of the BIRDS. A change in charge will indicate a subject of interest as landed on the landing pad and wake the bird analysis camera system. The simplicity of this approach for camera activation gives it a great advantage over the motion sensor, and the images captured upon sensing will have a much higher probability of being clear.

3.2.5.3 Bird Motion Sensor Comparison

The two options for the bird sensor to activate the bird camera were the PIR motion sensor and the capacitive touch sensor. Logically, a motion sensor would activate upon a bird approaching in the air. Taking this situation into careful consideration, we would run the risk of an image that is either motion blurred or just not clear enough because of the lack of control we have over where the bird is in relation to the camera sensor. Since we will be working with a fixed focal length camera, the object of interest, the bird, must be relatively close to a distance equal to the focal length away from the camera sensor where the image will be formed. Without control over where and when the bird will be sensed, the motion sensor option is at a serious disadvantage.

The second option we had was the capacitive sensor. With a touch-based sensor that senses upon a bird having landed on the landing pad of the feeder, we would have more of an ability to control the working distance of the imaging system. A fixed size landing pad along with a sensor built into that landing pad would make the bird sensing happen and the image be taken at a relatively fixed

distance, depending on how far apart we design the camera and landing area to be. As long as the focal length of the designed bird lens system is matched with this distance that the bird will be on the landing pad from the camera, the image that is taken will be of sufficient resolution. It is because of this ease of control over where and when the bird is sensed that we decided to select and implement the capacitive sensor as the sensing for the bird detection system of the BIRDS.

It's also worth noting that this capacitive touch sensor will be useful if we perform the same second stage of bird training and acclimation that the creator of the Crow Box used in development. The second acclimation stage for the Crow Box is a system that opens the food for the bird to feed on when the bird lands on the feeder. This stage slowly gives a bird the awareness of the system opening when it lands, as birds that have landed on the feeder for the first time will most likely be scared by the sudden movement of the door covering the food. This is yet another reason why the capacitive sensor was a cool and beneficial selection for the bird sensor of the BIRDS.

3.2.5.4 Laser Motion Sensor

In order to accurately detect if an object falls into the trash chamber, we will design a laser sensor system. If any object breaks the plane of the laser grid, a signal will be sent to the trash imaging sensor to take a picture of what has landed in the chute. This allows for a passive mode of the imaging sensor to use less power.

A system of mirrors will be designed to reflect the light from a laser source in different angles, ensuring that no trash can fall without breaking the path of light. The exact number of mirrors and at what angles they are to be placed will be determined during the design process. The laser source will be reflected onto a photo-detecting sensor. This sensor will either be a solar cell or a photodiode. Both convert photons into electrons, but there are pros and cons to each that will determine our final selection.

The laser source will need to be cost-effective and run at a low power to not drain power necessary for other functions of the BIRDS. A low power laser will also remove the dangers laser light could pose to users and animals alike. However, the power of the laser must be large enough selected sensor to convert the light into a signal. It must also produce visible light to correctly align the mirrors designed to create a laser grid.

One option for the photo-detecting sensor is the solar cell. Solar cells are designed to convert sunlight into electricity. They are optimized for capturing solar energy and typically have larger surface areas compared to other photodetectors. Usually, there is no voltage applied to the solar cell as its main attraction is the voltage it creates for power usage. This means there is only one operation for a solar cell to operate in: photovoltaic mode. A typical solar cell design can be seen in the figure below. Studies have shown that solar cells can be used to extract a high-speed data signal in an optical wireless communication link. Data speeds of 34Mbps have been observed while still generating maximum power in the cell.¹² This data speed is important for the BIRDS as a one-bit system will be designed to determine if an object breaks the laser grid and enables the sensor to go under a certain voltage. This drop of voltage would communicate to the MCU to take a picture of the trash chute for analysis.

¹² Zhang, 2015

Another option for the laser sensor is the photodiode. Commercially available photodiodes typically run at data speeds of 2Gbps with rise times anywhere from 400ns-10 μ s.^{13 14} Research has pushed data speeds to 25-50Gbps.¹³ Their rapid response time makes them ideal for applications that require real-time detection, such as optical communication and laser detection. A photodiode's high sensitivity makes them suitable for low-light sensing. They are also very compact and fit very well into any environment, and they are relatively cheap. The temperature sensitivity of photodiodes may cause their response to fluctuate.

A third and final option to act as a laser sensor is the photoresistor. They are typically used in night lights where the light will turn on when the room light shuts off. Photoresistors operate by changing resistance depending upon incident light levels. They are also cheap components and are very simple to use. The spectral bandwidth of a photoresistor is very wide, usually spanning from visible to infrared light. They also draw very little power. However, photoresistors typically have a response time of 2-50ms, much slower than photodiodes.¹⁵ Additionally, they do not last as long as other photo sensors, and they have very low sensitivity.

Table 3.2.5.3. Laser Sensor Comparison

| | Solar Cell | Photodiode | Photoresistor |
|--------------------|---------------|----------------|---------------|
| Data Rate | 34.2 Mbps | 2 Gbps | N/A |
| Rise Time | N/A | 1 μ s | 10 ms |
| Spectral Bandwidth | 400nm - 700nm | 800nm - 1100nm | 400nm - 900nm |
| Cost | \$15.50 | \$0.40 | \$0.20 |

After this comparison, we decided to use a photodiode for our laser detector. It is the fastest responding detector for the most optimal price. It can be seen in the table above that solar cells are not typically used for communication systems and therefore, data sheets do not provide rise times. Additionally, photoresistors are also not usually used in communication systems and most data sheets do not provide data rates for them.

We will design the layout of the laser and mirrors to shine the laser light onto a photodiode so that any object breaking the laser plane will cause a voltage drop in the diode. This drop in voltage will signal the camera to take a picture of the trash that was dropped into the chute.

3.3 Machine Learning Processor Boards

With our project, BIRDS, we will have to use a sensor to detect motion to then turn on higher computing devices that are machine learning enabled. The main use of machine learning in our

¹³ Ghandiparsi, 2018

¹⁴ Thor Labs

¹⁵ LEDnique

case is the use of image recognition. This means we will use computer vision and machine learning to correctly identify birds and trash. We will have to be able to detect if a bird has arrived in front of the housing, or some other kind of animal. After seeing that a bird has arrived, we must then see what the bird has dropped into the trash chamber and classify it as trash or not trash.

The core challenge we face lies in the real-time processing of images to make quick decisions. We require a device capable of giving a classification quickly and accurately after being presented with the image. Additionally, because we plan to run our device on battery, we must employ a device that is power efficient and has low-power or sleep technologies integrated into it. With these technologies all working together they must be able to give a classification of the image within less than a second to meet the 3 second starting input to finish output. For quick processing to happen, the image needs to be able to reach the processor quickly meaning it must be CMOS compatible.

With all this in mind, we investigated devices that support artificial intelligence, machine learning, and computer vision. These devices come in a range of different specs with how popular machine learning enabled devices are currently. Because of this there are many different things to take into consideration because there are so many different devices to choose from.

3.3.1 Options for products

In the following sections, we present some of the products that we have evaluated for their performances, weaknesses, and compatibility with machine learning applications. Each of these products use libraries specific to the device to support machine learning or computer vision in some way. These options all contain strengths and weaknesses that will be compared including cost, power, software, performance, and lead time. With chip shortages being more and more of a problem as time goes on, we may find the perfect device that meets all the requirements we want, but the lead time is just too long, and it is not feasible to acquire in time. To provide deeper understanding, we will be giving all the boards individual spotlights and then narrow them down to just a few boards that align with the requirements we are looking for.

3.3.1.1 Raspberry Pi 4

The first system that came to mind when it comes to small computing devices was the Raspberry Pi 4. The Raspberry Pi has been known for its low-cost computing for many years that can be used in many different applications of robotics, engineering, and computer science. With the Raspberry Pi being such a widely used system, there is tons of documentation on it with many open-source materials and tutorials on how to set up. The Raspberry Pi comes equipped with a Quad core 64-bit ARM-Cortex A 72, options of ram from 1 to 4 Gigabytes of LPDDR4 RAM, Bluetooth 5.0, and 28 GPIO pins. The board idles at somewhere around 540 mA and there is not any low power or sleep mode to this device. You can save power by shutting off certain peripherals that are not being used since we will not be using every piece of hardware on it. Disabling the USB Controller saves about 100 mA, the HDMI saves about 30 mA, and the CPU can be clocked down to save power depending on the speed. With all this put together the power should not be too much of an issue to this device when combined with external solar power to charge while its clock is slowed down. The Raspberry Pi uses the Raspberry Pi OS which is based on a Debian Linux distribution which some members of our team are already familiar with. This makes it much easier to write programs directly on the device rather than needing something to interface to it. Putting all this together at a starting price of \$35 USD sounds like it would be a great fit for our project. One of the biggest issues is that all the lower RAM models are sold out from most retailers leaving the

only options to be the 8GB models at \$75 USD. The Raspberry Pi also has a weaker GPU compared to some of the other comparisons on here, which is the bulk of where the processing needs to come from in our machine learning model.

3.3.1.2 Coral USB Accelerator

In researching for the Raspberry Pi, we came across something called the Coral USB Accelerator. This is a device that can link through USB as a coprocessor to the system. This enables high-speed machine learning on any device that can link through USB. The Accelerator has an on-board Edge TPU coprocessor that is capable of performing 4 trillion operations per second. This device uses 1 watt of power for every trillion operations that it does. This device supports all major platforms that are using an operating system such as Windows, Debian Linux, or macOS. This would be a good attachment to the weaker GPU of the Raspberry Pi to give it the boost in computation that is needed to run a trained machine learning model. The price for this Accelerator starts at \$59.99. This, along with the Raspberry Pi together, would work very well in processing but leaves the pricing to be quite high.

3.3.1.3 Coral Dev Board

Along with the Coral USB Accelerator we found a board that is another Google product named the Coral Dev Board. This is another one of Google's devices found under Coral.Ai which has many distinct products and documentation to go along with. The Dev Board comes with an on-board Edge TPU coprocessor that is comparable to the Coral USB Accelerator. This coprocessor offers 2 TOPS, which means it can perform 4 trillion operations a second and again at 1 watt per 2 trillion operations. The CPU is an NPX i.MX 8M SoC (System on Chip), a graphics processing unit, a video processing unit, 2 USB modules, 16 GPIO lines, and a machine learning accelerator as mentioned earlier. Putting the processor and coprocessor together you get a computing powerhouse. This board gives some of the best performance for its power across all the devices. The Dev Board is also using a complete Linux system using a Debian derivative called Mendel. The coprocessor is made specifically to accelerate TensorFlow Lite models which could potentially limit our use of pretrained models because they would need to be made using only TensorFlow lite. This all comes at a price starting at \$129.99 for the 1 GB version of this board. This is a decently high starting price, but due to it having such a powerful arsenal of machine learning hardware this will be kept in for consideration.

3.3.1.4 Nvidia Jetson Nano

Next up to compare is the Nvidia Jetson Nano. Nvidia is a company that has been known for its high standing in artificial intelligence for many years. The Jetson Nano does not shy away from this with its very powerful performance in machine learning. The Jetson Nano contains a 128-core Maxwell GPU. Maxwell is the name of the microarchitecture that Nvidia uses that allows for very good efficiency of its processors. The Jetson contains a 1.43 GHz Quad-core ARM processor which is very high performance for a small device such as this. It allows for a microSD slot for extra storage to be added. There are 2 models between the Jetson Nano that is a 2 GB of ram, and another model that is 4 GB of RAM. There is a header allowing for GPIO pins to be connected to other devices such as sensors and external hardware. There is no on-board wireless connection, however there is an extension for it to be added easily. The power consumption is between 5 and 10 Watts, which is a little on the higher end of devices. The Jetson Nano does have a sleep mode that it can enter that quickly resumes operations. This low power is just enough to power devices

connected to it and keeps all the logic for its pins rather than setting them to 0 Volts. The Jetson Nano runs a desktop environment named LXDE which is a lightweight operating system that requires very little resources to run. The Jetson Nano has support for many different deep learning frameworks such as TensorFlow, PyTorch, Caffe, Keras, and many more. This allows for a very smooth programming experience as we will not be limited to one framework. Very similarly there is very good library support, so this device really shines with its versatility. The Jetson Nano 4 GB version comes in around \$150 USD. This is very widely available and not sold out everywhere like some of the competitor boards. While the 2 GB version is advertised on Nvidia's website for support, finding a seller was a bit more challenging. With a very low starting price of \$59 USD, it seems all the sellers are sold out making this version not an option.

3.3.1.5 Arduino Nano 33 BLE Sense Rev 2

With microcontrollers Arduino was another one to come to mind very quickly. Our team has some experience with using Arduino for some smaller projects in the past, just with a less powerful microcontroller in their brand. This is why we thought to see if Arduino had some more powerful microcontrollers, and this is where we found the Arduino Nano 33 BLE Sense Rev 2. While it may not be as powerful as some of its competitors above it still has some key features to investigate. The Arduino Nano 33 BLE contains a 32-bit ARM Cortex CPU running at 64 MHz. It has 1 MB of flash and 256 kB of RAM, which is very small compared to other boards. The processor comes with Bluetooth pairing and ultra-low power consumption modes. The Arduino has the possibility of running Edge Computing application using TinyML. This uses the TensorFlow Lite framework which again limits it to only one framework making software a little bit harder to develop and maintain. Arduino has its own IDE that it uses to program its boards called Arduino IDE. There is a web version and a software version of this making it very easy to move between devices. Our team is familiar with this IDE, and it is a very high-level programming language with a lot of abstraction, making the software very easy to make. Arduino is very beginner friendly and has many different resources to get started and libraries to evolve the software to a more powerful state. The very appealing factors of the Nano that made it a very interesting choice is its low power applications. The Nano at maximum computing power with all its peripherals on and working draws a current on average of 6.3 mA. On the low end of the typical current consumption in low power mode, it draws only .95 uA. The Nano has a very low cost of \$40.50 USD and is in stock straight from Arduinos website. With its very low price and easy access this looks like a great product, however from its computational standpoint it will not be able to achieve the performance we are looking for. This means that the Nano will not be making it into the final product consideration.

3.3.1.6 Sipeed MAIX GO Suit

In our search for machine learning microcontrollers our team came across the Sipeed MAIX GO Suit. This is a product and brand that our team is unfamiliar with, however it does offer some good features that suit our needs well. The MAIX contains a dual-core RISC-V 64-bit processor. This is the first competitive processor that doesn't use an ARM instruction set. The RISC-V instruction set is an open-source instruction set architecture rather than the ARM proprietary architecture. The board also contains a KPU which is a general-purpose neural network processor. It offers the ability to use any activation functions, allowing for more versatility when it comes to the neural network framework. This KPU also has the ability to overclock to 800 MHz offering .5 TOPS. The MAIX supports the use of micropython allowing access to many different libraries to use as

well as using python to program the board. MAIX supports tiny-yolo, mobilenet-v1, and TensorFlow lite which are all frameworks to make neural networks. This allows for some more options in software when it comes to picking the network to train with. All its software is open source which means there will be tons of access to documentation. It has a very small footprint which makes it easy to integrate anywhere. Starting at \$40 USD it again looks like a very good option. All sellers appear to be sold out of this board at this time. With no access to buy this option is not able to make it into our final product consideration.

3.3.2 Product Comparisons

After carefully considering all our machine learning products above we have narrowed down our results to just three main options. These options consist of Google's Coral Dev Board, Nvidia's Jetson Nano, and finally the Raspberry Pi 4 with the Coral Accelerator as an extra attachment. These 3 options appear to be the most qualified and suited for the kind of processing we need in our project. The following sections offer a comparison of these 3 boards and where they do very well or fall short to the others.

3.3.2.1 Processing Power

In the table below we have the comparison of the CPU, Clock Rate of the CPU, GPU or TPU, and processor cache. Because of the nature of machine learning, the most important component in this will be the GPU or TPU as these are the best at performing matrix multiplications necessary for the network. These details will help provide the necessary details to choose which processor will have the best performance for what we are looking for.

Table 3.3.2.1. Processing Comparison

| | Coral Dev Board | NVIDIA Jetson Nano Developer Kit | Raspberry Pi 4 Model B + Coral USB Accelerator |
|------------|---|--|--|
| CPU | Quad Cortex-A53, Cortex-M4F | Quad-core ARM A57 | Quad core Cortex-A72 |
| Clock Rate | 1.5 GHz | 1.43 GHz | 1.8 GHz |
| GPU | Integrated GC7000 Lite Graphics + Google Edge TPU coprocessor | 128-core Maxwell @ 921 MHz | Google Edge TPU coprocessor |
| Cache | 32KB L1 instruction and data cache, 1MB unified L2 | 48 KB L1 instruction cache and 32 KB L1 data cache, 2 MB of L2 Unified Cache | 48 KB L1 instruction cache and 32KB of L1 data cache, 1MB of L2 Shared Cache |

The table above shows that the most qualified CPU for the task is the Raspberry Pi 4 Model B with its A72 processor. This is a newer generation of processor when looking at its predecessors that both the Coral Dev Board and the Jetson Nano both have. At 1.8 GHz, this processor seems to be the best in the CPU and Clock Rate for these categories. In the GPU category while the Raspberry Pi standalone doesn't have a mentionable GPU the coral accelerator gives it the edge with the same TPU as the Coral Dev Board. This makes the Raspberry Pi come out on top for the GPU category as well, with the only contingency that the TensorFlow Lite framework is used. The Jetson Nano

gives a more versatile performance allowing for more frameworks than just one. In the final category of cache, the Jetson Nano takes it with 2 MB of L2 cache with the Raspberry Pi shortly behind it with only 1. In terms of raw computational power, the Raspberry Pi 4 with the Coral Accelerator comes out on top.

3.3.2.2 Memory Comparison

The memory of each board is another important component to be able to determine if it is qualified to run many tasks in parallel and not need to wait on memory to free up. In the table below there is a comparison between the same 3 boards as above. This time we are comparing the memory on the system, to see which one will fit our machine learning needs. We also need enough memory to store the program on the system after the model has been trained. Another bonus would be if there is expandable memory so we can store things like images and data logs.

Table 3.3.2.2. Memory Comparison

| | Coral Dev Board | NVIDIA Jetson Nano Developer Kit | Raspberry Pi 4 Model B + Coral USB Accelerator |
|-------|---|--|--|
| RAM | 1 or 4 GB LPDDR4 Memory | 2 or 4 LPDDR4 Memory | 1, 2, 4, or 8 GB LPDDR4 Memory |
| Flash | 8 GB eMMC, with a MicroSD slot for expandable storage | 16 GB eMMC, with a MicroSD slot for expandable storage | Expandable MicroSD slot for program and Operating system |

All these options have comparable memory and flash. Since they all have expandable MicroSD slots all of these are great options for the flash memory that we need. In terms of RAM the only one that has an advantage is the Raspberry Pi 4, as it has an 8 GB option for memory unlike the other 2 that only go up to 4. When looking for these different products many retailers were sold out of their lower RAM options, leaving only their higher versions of RAM devices to choose from. This means that the Raspberry Pi 4 has a slight edge on the others in terms of memory as well, making it the best choice for our needs in this category.

3.3.2.3 Pricing

Like with every engineering process, there is always a trade-off between performance and price. This principle also applies when selecting a machine learning controller. We must try to keep everything as cheap as possible so that we can meet our funding provided by our sponsor. Our primary objective is to maintain cost-effectiveness to align with the funding provided by our sponsor. Simultaneously, we must ensure that the product we procure fulfills our processing requirements both effectively and efficiently.

As a collective we have chosen a philosophy that functionality must come first over price. This means that while price is important, we must make sure that every requirement is met properly. With this understanding the pricing is important, however it is valued a little bit less than functionality and versatility.

With these things taken into consideration, we have the prices as found at their minimum on seller websites. The Coral Dev Board starts at \$129.99 with the 1 GB version and \$149.99 for the 4 GB version. The NVIDIA Jetson Nano comes out to be \$149 for the 4 GB version and the 2 GB version

doesn't exist on seller websites anymore. The Raspberry Pi 4 at 1 GB of RAM comes out to be \$35 all the way up to \$75 for the 8 GB version. The Coral Accelerator starts at \$59.99. This paired with the Raspberry Pi 4 can range from \$95 to \$135. This makes the Raspberry Pi option the best priced even with the added expense of the Coral Accelerator.

3.3.2.4 Product Software and Setup

Hardware is a very important topic going through each of these small devices, however another important thing to note is that each of these devices uses its own special software with it. Either the initializing of all the operating system for the first time or how to program the board itself. This section will cover different features and drawbacks on these three boards.

For the Jetson Nano Developer Kit there is a great tutorial that gives an Introduction, Preparation for setup, how to Write an Image to the SD card, Setup and First Boot, Next Steps, and Troubleshooting all on one page with a getting started guide. In starting off it is very simple for the first boot of the Jetson Nano. First the microSD card that is being used just needs to have the Jetson Nano Developer Kit SD Card Image formatted to it. This is as simple as just downloading the software from NVIDIA's website and then using another piece of software to format the microSD. From here just connect keyboard, mouse, and display to see the boot and all the initial options to choose from. Since there is a Linux operating system running on the device, programming it will be very easy as we can write the software directly on the device itself. The JetPack SDK is said to be NVIDIA's solution for building accelerated AI applications. This comes with a complete set of libraries for acceleration of GPU computing and computer vision which is perfect for the application we are using it for. Some of the key features of this SDK include TensorRT, cuDNN, CUDA, Computer Vision, CUDA Toolkit. With this many libraries it will be very easy to find something that fits our need rather than having to tailor specific things to our specific needs. There is a whole library of Jetson Community Projects that will have some examples and some software that can help us achieve what we are trying to do with our object recognition.

The Coral Dev Board also has a great getting started tutorial right through their website. This has all the same steps as the Jetson Nano on their site starting with requirements all the way down to the next steps. Unlike the Jetson Nano that runs the operating system straight from the microSD card, the Coral Dev Board takes the microSD and writes it to the flash memory after its first use. This is also as simple as downloading the required software onto the microSD chip, then bootup the device with the microSD in the board and it will flash to the chip itself. The tutorial has a few extra steps to setup once booted as the operating system is not a graphical user interface system like the Jetson nano. This adds a bit of difficulty to the setup because most devices we are used to working with aren't only command line interfaces. The Coral Dev Board works with PyCoral API that utilizes its Tensor Processing Unit built into the board. This hardware only works properly with TensorFlow Models that are specifically meant for the Edge TPU. Because of this our choice of framework is limited, which in turn could limit some of our software to be forced into a box that we will not be able to adjust.

With the Raspberry Pi alongside the Coral Accelerator, we are introducing multiple things to have to worry about in software. We will be having to setup and properly initialize 2 different pieces of hardware to work together. The Raspberry Pi itself has a beginner's guide that is very comprehensive, but also a bit overwhelming at first with it having close to 250 pages. Similarly, to the other boards the microSD has to be loaded with the operating system that is going to be used

then written to the Raspberry Pi on its first boot. The operating system used by Raspberry Pi that is heavily supported is the Raspbian Operating System. This is another Debian-based operating system that has a graphical user interface making setup a bit easier. The Thonny Python IDE is already on the system allowing for easy development of Python applications. Setting up the Coral Accelerator to run alongside the Raspberry Pi actually isn't very hard to do at all. All that is needed is to make sure that it is in a USB 3.0 to utilize the higher data rate than the other USB slots. There isn't a setup for the device it is just plug it in and when the script is going to be run just add `--edgetpu` to the script argument and it will utilize the TPU. Since this is using the same TPU as the Coral Dev Board this again limits us to using only TensorFlow Lite models as that is what the hardware is for.

When it comes to programming and training different machine learning models, the actual device itself will not vary too much. With Google having a cloud-based programming service named Google Collaboratory, every program can be written and computed in the cloud. This service uses Jupyter notebooks to further simplify and organize Python Code. This gives us easy access to programming from any device, with free access to a Google GPU or TPU that can train models in reasonable amounts of time. This GPU does have a limit on how long you can use it, so there is a small premium to pay to extend the time with the GPU. After writing everything being done running and testing it can be downloaded as a Python script making it easy to access from any device. Google Collaboratory comes with many libraries already installed making it as simple as just importing whatever library is needed. For any library that isn't already installed, there is a simple command to install the library to Collaboratory. This will be our main source of programming when it comes to all of the machine learning applications.

Our machine learning applications will most likely use a pretrained model in some way, as these are generally very powerful and very accurate. We will go into more detail in a later chapter, but this is done through something called feature extraction. A very popular computer vision model that is open sourced by Google is called MobileNet. MobileNet is very powerful, but it is also a bit more computationally intensive so we need to make sure that the board can handle these speeds. As shown in the table below, the performance of these boards all meets the requirements. Some are faster than others, but since these are all rendering videos, they should more than meet the requirements of our project.

Table 3.3.2.4 Benchmarking for Machine Learning Frameworks

| Model | Framework | NVIDIA Jetson Nano | Raspberry Pi 4 B + Coral Accelerator | Coral Dev Board |
|--------------|------------|--------------------|--------------------------------------|-----------------|
| MobileNet V1 | TensorFlow | 61.6 | 14.9 | 15.7 |
| MobileNet V2 | TensorFlow | 72.3 | 18.2 | 20.9 |
| ResNet-50 V2 | PyTorch | 27.7 | 52 | 56 |
| ResNet-18 | PyTorch | 200 | DNR | DNR |
| YOLOv3-320 | Darknet | 40 | DNR | DNR |
| VGG – 19 | MXNet | 100 | 200 | DNR |
| Unet | Caffe | 55.5 | 200 | DNR |

This is the amount of time per inference in milliseconds. The lower the number the better.

These results are all based on taking a very big test image at 3888x2915 pixels. This image was taken and preprocessed down to a 300x300 pixel image, then passed into the model. With these times we see that the Raspberry Pi 4B with the Coral Accelerator is the fastest of all of the boards when using the MobileNet models. This is very apparent when looking at the MobileNet models because these are TensorFlow models that the Google TPU is specifically meant to perform so highly on. This would restrict us to using TensorFlow to get the most out of the hardware we have which could cause some problems in the future.

3.3.2.5 Product Availability and Miscellaneous Features

In addition to all of the different processing features there is some things that sway us to some boards over the other. This section will highlight a few of these features here that allow us to come to our final decision.

We will be using a USB interface to be able to communicate with the CMOS, so it is important for our device to have enough ports to support the 2 cameras. With this in mind in order to make sure that the device gets the data as fast as possible to process, USB 3.0 speeds will do better to give the data over. Since we have 2 cameras, we would like there to be at least 2 USB 3.0 ports and at least 1 USB port of any kind to be able to interface a device to see diagnostics, and food levels. The Jetson Nano has access to 1 USB 3.0 and 3 USB 2.0 ports totaling to 4. The Raspberry Pi 4 B has access to 2 USB 2.0 ports and 2 USB 3.0 ports. This is deceiving because it also needs a USB 3.0 port in order to properly interface the Coral accelerator, allowing for only 3 USB ports in total to use. The Coral Dev board is a little less straightforward with its interfacing hardware. There is a USB 3.0 Type C, USB 3.0 Type A and USB 2.0 Micro-B. This means the Coral Dev board would require a USB hub to properly work with our cameras.

Wireless technology such as Wi-Fi or Bluetooth might also be useful in interfacing devices. The Jetson Nano does not come with built in Wi-Fi but has a peripheral that can be added in the future should we choose to need Wi-Fi. The Jetson Nano does however have an ethernet port so it can still be connected to the internet. Similarly, there is no Bluetooth support on the Jetson Nano without an add on. If we need either of these wireless connections in the future it is as simple as adding one thing to give both Wi-Fi and Bluetooth access. The Raspberry Pi 4 comes integrated with both Wi-Fi and Bluetooth already on the device. This means that there would be no extra need for added peripherals to connect any devices wirelessly. The Coral Dev Board comes with both Wi-Fi and Bluetooth as well. This means that in terms of wireless connections both the Coral Dev Board and the Raspberry Pi 4 come out on top.

3.3.3 Machine Learning Product Choice

After careful consideration of our options, our team decided to move forward with NVIDIA's Jetson Nano. In terms of performance, it is slightly lacking behind the other two, but it makes up for its versatility. We don't know what issues may arise in the later times of testing, so versatility goes a long way in making this decision. The Jetson Nano is more than capable of holding its own to the competition. This system comes in at \$150 USD and will be used in all of the machine learning applications with the image recognition of both the birds, and the trash. The NVIDIA TensorRT SDK that uses CUDA packages so many different components together all in one making it very easy to work with and open to many different applications. Another very big reason in making this decision is at the time of purchasing there is no sellers that have any other options

in stock. To avoid having very little time to work with and debug our project, we wanted a board that could get here in a reasonable time. In order to achieve this the Jetson Nano was the only one that could fit that description. Every other board was unavailable or had incredibly long lead times making it impossible to choose given our circumstances.

3.4 Optical Systems

To accurately detect the animals that encounter the BIRDS, we must build an optical design that gives our machine learning processor board sufficient images to determine what animals are activating the system and what objects they bring to it. The ultimate goal is to only have our system advance in its processes if a bird brings trash. To achieve this, two different lens systems will be built to focus light into their respective sensors. These sensors will be hooked up to the processing units for image recognition to take place.

To determine the best sensor to be used in both of our optical systems, we researched CMOS (Complementary Metal-Oxide-Semiconductor) and CCD (Charge-Coupled Device) sensors. Both CCD and CMOS image sensors convert light into electrons by capturing photons with thousands of light-capturing wells called photosites. When an image is being taken, the photosites are uncovered to collect photons and store them as an electrical signal.¹⁶ Each sensor is discussed in detail below.

3.4.1 CMOS Sensor

CMOS sensors are designed similar to most integrated circuits, almost 90% identical to computer chips.¹⁷ Each pixel in these sensors has its own amplifier and readout circuitry allowing for parallel reading of pixel values. This means that CMOS sensors are capable of faster readout speeds and lower power consumption compared to CCD sensors. There are also no complex time clocks used. They are known for their lower power consumption, which makes them suitable for battery-operated devices like the BIRDS CMOS sensors can achieve high frame rates and are used in applications that require rapid image capture. This is mainly due to parallel reading previously discussed. The image quality of CMOS sensors has been improving over time, but they do not have the same capabilities as CCD sensors in this area. CMOS sensors also tend to be more cost-effective to manufacture. Because of this, they tend to be the preferred choice for consumer electronics and many different applications. Additionally, CMOS sensors allow for more compact designs.¹⁸

3.4.2 CCD Sensor

In a CCD device, the charge is transported across the chip and read at one corner of the array, and an analog-to-digital converter turns each photosite's charge into a digital value.¹⁶ CCD sensors send the electrical signals through a series of capacitors and registers before being read out sequentially. This serial readout process results in slower readout speeds and higher power consumption. CCD sensors are therefore less suitable for battery-powered applications but still valuable in scenarios where power efficiency is not a primary concern. They typically consume 100 times more power than CMOS sensors. The slow readout speeds limit their use in high-speed applications. When dealing with image quality, CCD sensors are preferred in applications where

¹⁶ Teledyne Flir, 2021

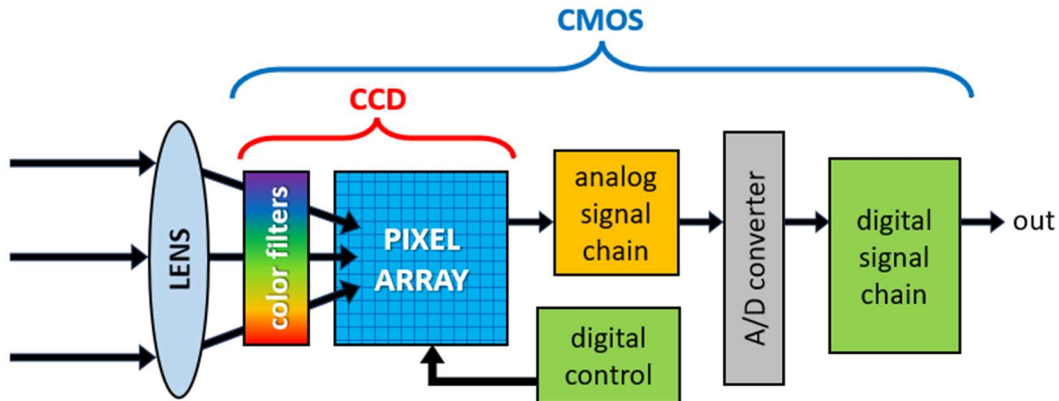
¹⁷ OPI, 2009

¹⁸ SVS-Vistek

the best resolution is needed, such as scientific imaging and astronomy. These sensors are typically more expensive to manufacture, making them more common in specialized industrial imaging applications.

3.4.3 Sensor Comparison

Figure 3.4.3 Comparative schematic of CMOS and CCD data acquisition



After conducting a thorough investigation on CMOS and CCD sensors, we decided to choose CMOS sensors to implement into our imaging systems because of cost and power constraints. It can be seen in the chart below that CMOS sensors draw less power than CCD sensors, which is a vital capability for the B.I.R.D.S. CMOS sensors are also typically cheaper and more user-friendly. The figure above gives a brief synopsis of the main hardware differences within the two sensors. As said before, the ability for the CMOS sensor to pixel values in parallel leads to its faster readout time.

Table 3.4.3 CMOS & CCD Sensor Comparison

| | CMOS | CCD |
|-------------------|------------------|------------------|
| Readout Noise | 5 e ⁻ | 3 e ⁻ |
| Power Consumption | 2.5V | 12V |
| Readout Time | 10ms | 500ms |
| Price | \$50 | \$200 |

3.4.4 Interfacing

The optical systems of the B.I.R.D.S. must interface with the electronic systems in order to process the data and activate higher order functions in the B.I.R.D.S. To effectively connect the CMOS

sensors to the Jetson Nano for image processing, we must select the proper interfacing cable to transfer data of high resolutions at high speeds.

3.4.4.1 MIPI CSI-2 Interface

MIPI (Mobile Industry Processor Interface) sensor interfaces are a popular choice for applications where high data throughput, power efficiency, compact design, and standardization are essential. The MIPI CSI-2 (Camera Serial Interface 2nd Generation) standard is a high-performance, cost-effective, and simple-to-use interface.¹⁹ It offers a bandwidth of 10 Gb/s and faster speeds than USB 3.0. There are four image data lanes with each lane capable of transferring data up to 2.5 Gb/s. However, MIPI cameras rely on extra drivers to work.¹⁹

3.4.4.2 USB 2.0 Interface

The USB interface is well-known for its plug-and-play capabilities. The simplicity and cost-effectiveness of it speaks for itself. Still, USB 2.0 is an older version, and there are technical limitations. This specific interface is beginning to dwindle, and several of the components involved are now incompatible.¹⁹

3.4.4.3 USB 3.0 Interface

USB 3.0 has now begun to replace USB 2.0. The industrial standard of vision embedded systems, USB 3.0, also improves its ability to capture images of high-resolution at high speeds.¹⁹ It is one of the most cost-effective interfaces for machine vision. The latest CMOS image sensors, commonly used in compact cameras with high data throughput, make good use of the high bandwidth, up to 5 Gb/s.¹⁸

3.4.4.5 Interface Selection

We chose a USB 3.0 interface as it is the cheapest option yet still reliable to accomplish our objectives. The extra drivers for the MIPI interface would draw more power and cost more to process our images. The simplicity and easy use of the USB 3.0 interface makes it the best selection. There also wasn't a significant need for extremely high-quality images, and the USB 3.0 interface gives sufficient resolution for image processing.

¹⁹ Kumar, 2021

Figure 3.4.4 Interfacing Comparison Chart

| Features | USB 3.0 | MIPI CSI-2 |
|---------------------|-------------------|---|
| Availability on SoC | On high -end SoCs | Many (Typically 6 lanes available) |
| Bandwidth | 400 MB/s | 320 MB/s/lane 1280 MB/s (with 4 lanes)* |
| Cable Length | < 5 meters | <30 cm |
| Space Requirements | High | Low |
| Plug-and-play | Supported | Not supported |
| Development Costs | Low | Medium to High |

3.4.5 Bird Lens System

To both alert the system of a bird that has been identified and give our image recognition software an image of the bird with sharp enough focus for identification, a proper lens system will be required to effectively focus light into the camera's sensor. Given the measurements and specifications that our housing setup would create, we set off to determine the most efficient way to give our software a detailed enough image for processing. Our decision to build a camera for imaging stemmed mostly from our desire to tune the specifications closest to those which we desire for our setup's optical design. The distance from the camera, which will be directly attached to the housing, to the point of best focus of a bird on the landing pad, which will be a specified distance from the main housing, and the desired field of view that would fully image the bird will ultimately be the determining factors for the specifications of the bird camera's lens system.

In the initial research for the optical design of the bird camera's lens system, we modeled the camera design after that which is typical of high-resolution cameras. Specifically, the lens system we planned to design resembled the typical multiple lens system in modern, high-quality cameras. Our goal was to utilize the quality of such a system while adjusting according to the specifications of our system, but we quickly realized the complexity of this approach, and we also realized there wasn't a need for such an approach. The complexity of designing a multiple lens system lies in the precision with which the optical components of such a system need to be placed and aligned to give the best and sharpest images. And since the addition of more lenses only multiplies the magnification with each added lens, we concluded that only one lens is needed if that lens provides the desired magnification for our system. Given that we also don't need extremely high-quality images to perform image recognition with a certain percentage match that represents a certain confidence level, a single lens is sufficient for our camera's optical design. Therefore, the only features of our system will be the object or subject to be imaged (the bird), a CMOS sensor, and a lens placed at optimal position in relation to the bird and the sensor.

3.4.5.1 Bird and Sensor Measurements

Before considering the components that would be needed for the external imaging system for a bird interacting with the system, many factors needed to be considered. One significant factor is

the desired dimensions of the system, including the key measurements in lens system calculations. These key measurements include object distance, image distance, object size (horizontal and vertical), and image size (horizontal and vertical), and they determine the desired focal length and position of the lens.

Object distance (d_o) refers to the distance between the object (a bird in this case) and the front principal plane (FPP) of the lens system, and it would be roughly the distance from the front area of the bird landing pad to the front of the lens system. It is important to note that it is rare for the object distance to be measured from the physical front of the lens itself, as the front pupil, or front principal plane, of most lenses differs from the front of the actual lens. On the other side of the lens, image distance (d_i) refers to the distance between the back principal plane (BPP) of the lens system and the image, which would be roughly the distance from the back of the lens system to the sensor area on the CMOS, but this is only an approximation. The same note that was made about the object distance not typically being measured from the physical lens applies here for the image distance. Going back to the front of the system, object size refers to the dimensions of the object being imaged by the system, which would be the horizontal and vertical size of the bird being imaged. To capture a full image of the bird, with room for an offset in the setup in the case of the bird not landing directly in the center of the system's field of view (FOV), our object size will be slightly bigger than the size of the bird. And lastly, at the end point of the system, image size refers to the size of the image being focused onto the CMOS sensor, which refers to the dimensions of the image created at the image distance. The dimensions of the image created at the image plane for our sensor happen to be very small given the desired demagnification effect for our system.

It is important to note that the typical sensor size of a CMOS will mostly determine our image size, as we will be filling the sensor mostly with the image of the bird to give the best possible resolution. Specifications for the desired detail of images captured of birds, specifically the minimum detail size needed for a certain percent match, are included in sections on image processing. A diagram showing the key lens system measurements that were just outlined, along with more geometric optics, is shown in Figure 3.4.5.2.

3.4.5.2 Focal Length and Field of View

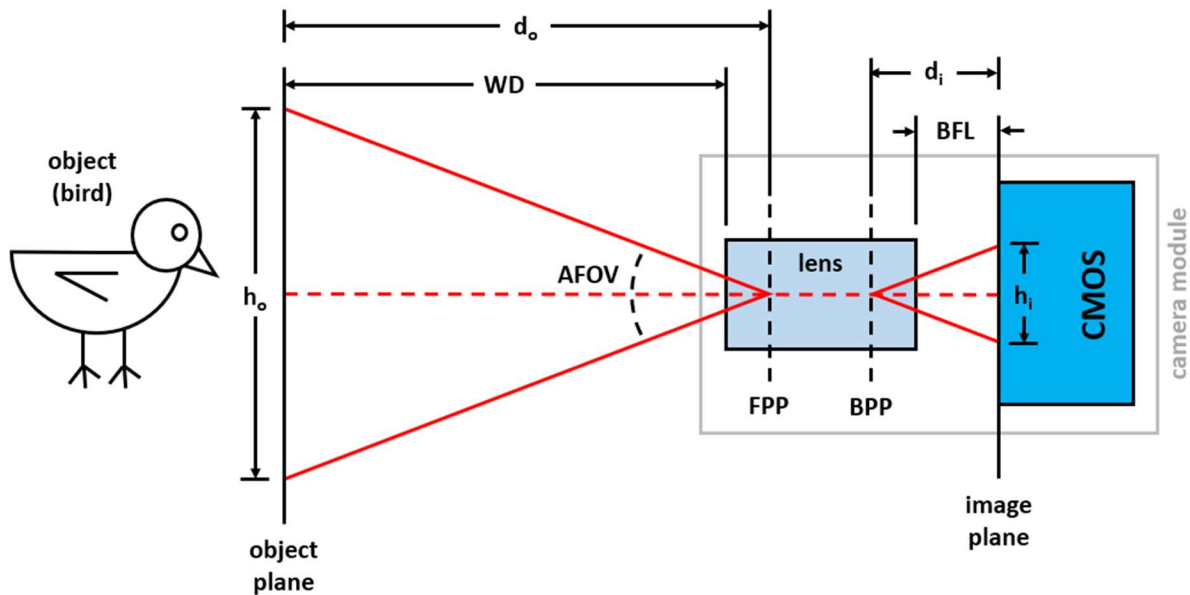
As explained previously, before optical components were to be purchased for the bird camera system, an understanding of the specifications of our overall setup was needed. Specifically, the object distance, image distance, object size, and image size were all measurements that needed to be considered. The figure below shows the relationships between those measurements in the object and image dimensions.

First, we must consider the object dimensions. The working distance (WD) is the distance from the object plane to the front surface of the lens system, and it's the distance at which our system gives the best focus for the bird that will be imaged. The field of view (FOV) shown is the same as the object height (h_o), and when measured in both the horizontal and vertical directions, it represents the width and height, respectively, of the best focused area of the object. The FOV is directly influenced by the angular FOV (AFOV), or the total acceptance angle of light from this best focused area for the lens. Ensuring the AFOV of our system is wide enough to capture the full image of a bird on the landing pad is a crucial aspect of our project.

Next, we must consider the image dimensions. The back focal length (BFL) is approximately equivalent to the focal length of the lens. It's measured from the back of the lens to the image

plane. On the other hand, the image distance is the distance from the BPP to the sensor. When the object's distance is much larger than the image's distance, the incoming light rays are nearly perpendicular to the optical axis of the lens system, which is characteristic of a system where the object's distance is considered infinite. In this scenario, the outgoing light rays behind the lens are focused to the focal point of the lens, giving the sharpest image at the focal length of the lens. Our lens system will act in a similar fashion, but with finite distances used in the calculation for the focal length of the lens. Lastly, the height of the image (h_i) is equivalent to what was referred to as the image size, and when this image size is measured in both the vertical and horizontal dimensions, it gives the dimensions of the image that will be cast onto the CMOS sensor. The image size will be roughly equal to the sensor size to give the highest resolution, or minimum detail size for each pixel on the camera sensor. This desired minimum detail size will be discussed later, as it is impacted by the matching required by our image recognition. The sensor size will be made sure to be slightly more than the desired image size so that the full image can be captured, specifically so variations in object size will be accounted for.

Figure 3.4.5.2 Conceptual bird lens system



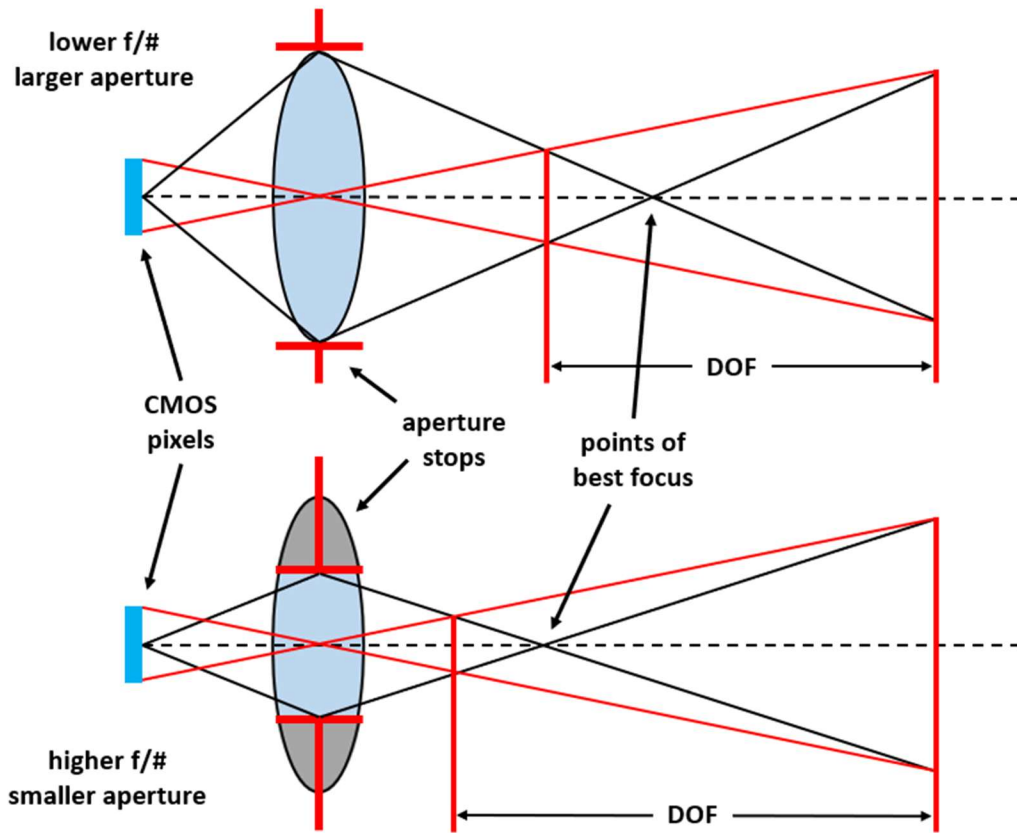
Now that all measurements have been considered, the next step in developing a design for our lens system is considering the relationships between these measurements. The magnification relationships of optics define the total magnification for our single lens system as the proportion of the image size to the object size. This would be calculated by dividing the width or height of the image by the width or height, respectively, of the object. The lens magnification is also approximately equal to the back focal length divided by the working distance. Setting those proportions equal to each other and solving for the focal length allows us to have a formula for the desired focal length of our lens as a function of the sensor size, working distance and field of view. Therefore, the impact of the field of view, given the sensor size and distance at which the camera will be working from, on the focal length of the lens that we should purchase is clearly shown.

3.4.5.3 Aperture Size and Depth of Field

Another important feature of our lens system to consider is the aperture size of our lens, which affects the depth of field of our imaging. Since the optical design of our lens system does not feature the mechanics required for an auto-focusing lens, the ideal position of focus for the bird will be fixed. This means that variation in the position of the bird with respect to the plane of best focus, which can't completely be controlled, will need to be considered. This problem poses a challenge for the design of the physical hardware of the BIRDS as well, since the landing pad will need to be designed in a way that minimizes the variation in the position of the bird and forces the bird to land closest to the point of best focus. Discussion of hardware design that takes these factors into account is included later on in the report. When researching lens design, we found that the answer to minimizing this problem of focusing without an auto-focusing mechanism lies in the aperture size of the lens.

As shown in Figure 3.4.5.3, a smaller aperture, which corresponds to a higher f number ($f/\#$), yields a longer depth of field in the object domain. In short, the depth of field is measured between the intersections of the cone of light representing the resolution of the system (in red lines) and the ray trace for the object location of the best focus (in dotted black lines). Since the resolution and contrast of the image are negatively affected as the object is blurred when moved to be in front of or behind the best focus, the depth of field of a system must be defined along with our system's desired resolution and contrast. Therefore, the minimum resolution or detail size needed by our software to recognize a bird with a certain confidence will be what determines our margin for error within the depth of field. Choosing an aperture size with a depth of field that gives this margin for error will be key. It is also important to note that, as can be seen in the figure below, the depth of field behind the point of best focus is much longer than that in front of the same point. To take this into account, a design that exaggerates the plane of focus to be at a point that leaves more of the bird at or behind the point of best focus of the system will be better than a design that has the bird closer to the lens system and within the narrower front of the depth of field.

Figure 3.4.5.3 Geometric diagram of depth of field



It's also worth noting that the lens' focal length itself also has a notable effect on the depth of field of the lens system. The longer the focal length of the lens, the smaller the depth of field. The shorter the focal length, the larger the depth of field. With a desire for a larger depth of field, we will use a lens with a small focal length, most likely around 5 to 6 mm or smaller, preferably.

3.4.5.4 Products

When researching applicable products for our bird lens system design, we decided to purchase and analyze a typical CMOS camera with a lens system to get an idea of how we could replicate and fine-tune such a setup for our project. We anticipated that having a working camera, working with it hands-on, and seeing results would serve as a beneficial observation stage for our own optical system design for the bird lens system, and the trash lens system to follow. Cameras compatible with the Jetson Nano were researched, and we took note of the various AFOVs and resolutions of the cameras. CMOS sensor modules with standard lens module encasements were found to be a promising product option for our camera designs, since choosing and integrating our desired lens and aperture size would work well with an empty slot for screwing in a desired lens module. This approach fits in perfectly with the design research we did for our bird and trash camera systems.

3.4.6 Trash Lens System

Creating a clear enough picture for the software to determine if an object dropped into the trash chamber is indeed trash, a lens system will need to be designed to focus light into the sensor. Our basic goal is to be able to detect cigarette butts from other objects. Once an image is taken, the data will be transmitted to the Jetson Nano through a USB 3.0 cable to run the image through a neural network for machine learning.

Capturing a picture in the trash chamber will require a few elements: the object itself, an LED to illuminate the object, a single focusing lens, and a CMOS sensor. Typical trash imaging and sorting cameras are designed to gather hyperspectral data on trash. These systems identify and separate different materials, such as plastics, textiles, metals, glass, paper, and cardboard, based on their chemical structure.²⁰ (1)

Many companies have built and are designing imaging systems that can automate the waste sorting process. This reduces errors and decreases the time of sorting. For example, Specim is a company devoted to building hyperspectral imaging solutions. The way their cameras work is using a line scan push broom design. In it, a small slit is utilized to measure accurate spectra of the object.²⁰ Their systems also display images with numerous color bands compared with the three band RGB cameras most used today. Our design will not include these additional components and features as we are simply attempting to read the outline of objects, namely a cigarette butt.

There are many different types of lenses to use in a lens system. Specifically, lenses can be classified into two main categories, converging (positive) and diverging (negative). In general, positive lenses collimate light to a focused point called the focal point, and negative lenses cause the light to spread behind the lens.²¹ Tied with lenses is what is called the conjugate ratio. It is defined as the ratio between the distance from the object to the lens and the distance from the lens to the projected image.²¹ Our design will deal with an infinite conjugate ratio as the distance of the objects we will image will be orders of magnitude greater than the focal length. As seen below in Figure 3.4.6.1., we will use a plano-convex lens because it is the best positive lens to deal with an infinite ratio. The asymmetry of the plano-convex lens minimizes spherical aberration in situations where the object and image are located at unequal distances from the lens. The optimum reduction of spherical aberration is the object placed at infinity and the final image is a focused point.²²

When multiple lenses are added to any design, more factors are added into the configuration of the system. Exit pupils must match entrance pupils, or put simply, light out of one lens must all converge into the next lens. Magnification of the desired images is also increased, and certain aberrations can be fixed with a specific ordering of lenses.

Figure 3.4.6.1. Ideal Conjugate Ratio for Lens Shape

²⁰ Specim

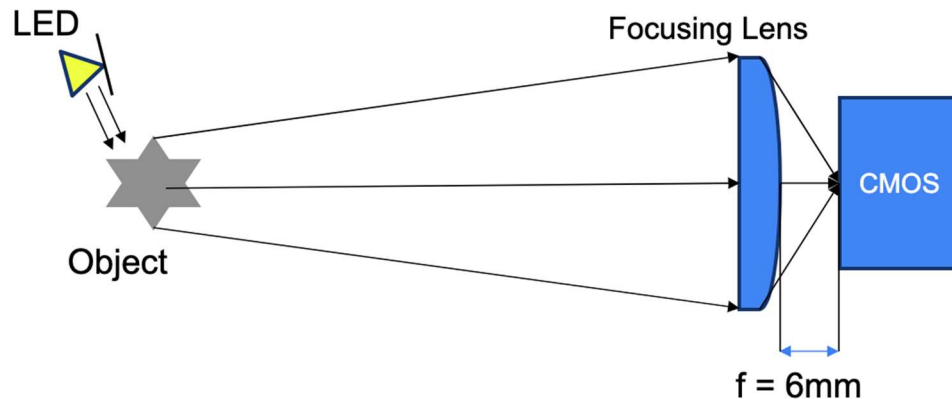
²¹ GlobalSpec

²² MKS Newport

| Lens shape | Ideal conjugate ratio |
|----------------------|---|
| Biconvex | < 5:1 |
| Plano-convex | All |
| Plano-concave | Infinite, larger finite (> 5:1) |
| Biconcave | < 5:1 |
| Meniscus | Varies; dependent upon curvature and polarity |

As seen in Figure 3.4.6.2., our design will consist of a single plano-convex lens to mitigate complexities and best image the trash.

Figure 3.4.6.2. Diagram of Trash Lens System



3.5 Development Boards

Along with the microcontroller choice, it is also important to have a development board capable of easy testing and prototyping. These development boards have access to many different features that help the process before putting everything on to a printed circuit board. These boards have features like access to on board LEDs, an on board lcd displays that are very easy to use with the module of choice, and they come with pin headers already on the board for easy access to different functions of microcontroller. With the proper selection of development board, the prototyping phase will be much faster to test and work out different functions and make sure that all the sensors and devices properly interface with the microcontroller choice that we make. The correct selection of development board will also influence the selection of our microcontroller as we want to test all of our devices with the same microcontroller that is being used in the development board as well as the one, we choose for our printed circuit board.

3.5.1 Arduino Mega 2560

The Arduino Mega 2560 is a microcontroller sitting under the Arduino branding. Arduino is used very commonly among many electronics systems with it having access to many different libraries using the Arduino IDE. The Arduino IDE is open source and very easy to perform logical operations as there is high levels of abstraction. This development board has access to 54 digital input and output pins that operate at 5 volts with a 20-mA recommended current rating. These pins have a 20 to 50 kilohm pull-up resistor that have a maximum rating of 40mA so that no permanent damage happens. The 2560 board also supports all the major communication protocols between microcontrollers such as UART, I2C, and SPI. The board supports both a hardware reset button as well as an automatic software reset that will force the program to start back at the beginning of the bootloader. The Arduino Mega 2560 comes with 54 general purpose input/output pins that can be used for many different functions. Of the 54 of these pins, there are special pins that support serial data input and output, external interrupts, PWM (pulse width modulation) which allows for digital output to look like an AC signal, SPI, and a built in LED. This development board comes with 256 Kilobytes of flash memory of which 8 KB is used for the bootloader, 8 Kilobytes of SRAM, and 4 Kilobytes of EEPROM memory. The on-board clock runs at 16 MHz driving the main microprocessor. The input voltage range is from 6 to 20 volts with a recommended of 7 to 12 volts so that everything functions properly as expected. This development board supports different varieties of sleep modes which turn off certain peripherals as well as turning off the processor. Once the processor is off it can be woken up by different types of interrupts that can all be interfaced through the Arduino libraries.

3.5.2 Arduino Uno

The Arduino Uno is in the same microcontroller family as the Arduino Mega so it will share a lot of the same specifications between them. The Arduino uno is generally used for an introductory system into robotics or programming embedded systems. It is using the Arduino IDE as its development environment with all of the same access to the different Arduino libraries. This development board uses the ATmega328P. This is a much smaller microcontroller with 14 general purpose input/output pins that 6 of these can be used with a pulse width modulation which makes a digital signal turn into a square wave that modulates the duty cycle to create a kind of AC signal. This board is also running with a 16 MHz clock on the development board that drives the main processor. This board supports USB connection as well as ICSP header, a reset button to allow the program to start from the beginning of boot. The Arduino Uno is the very first revision in the USB versions of Arduino as “Uno” stands for one. The Uno board also supports all the major communication protocols between microcontrollers such as UART, I2C, and SPI. The Uno also supports Automatic software resets just as the Mega above does. The Uno has 32 KB of flash memory, and .5 KB is being used by the bootloader. The Uno contains 2 KB of SRAM and 1 KB of EEPROM memory. All of these are smaller than the Mega, but the board is also cheaper, as it is more of an introduction to robotics. The input voltage range is from 6 to 20 volts with a recommended of 7 to 12 volts so that everything functions properly as expected. This development board supports different varieties of sleep modes which turn off certain peripherals as well as turning off the processor. Once the processor is off it can be woken up by different types of interrupts that can all be interfaced through the Arduino libraries. The Arduino Uno operates at 5V making it very easy to interface as with most electronics, a lot of devices like to use 5V.

3.5.3 MSP430FR6989

The MSP430FR6989 is a very popular and very powerful microcontroller dev board in the MSP430 series. This is a system that we have a good bit of experience with because of a previous class on “Embedded Systems” where we learned how to use the MSP430FR6989. This microcontroller is also being driven by a 16 MHz clock on the development board. This board also has access to a 32K crystal that can be used to time different aspects at a slower frequency to allow for timing without having to count rapidly with a fast crystal. The MSP430 supports 128 KB of flash memory alongside 2 KB of RAM. The MSP430 has a ton of general-purpose input/output pins with 83 different pins available. The MSP430 can be programmed using Code-Composer Studio. This is an IDE that allows for debugging, programming, and writing code for a variety of TI related projects. This IDE uses C as its main programming language. The C standard is not made for embedded systems such as these so particular libraries need to be implemented in order to access memory mapped modules. The pro to using C as the main programming language is that it allows us to program much closer to what the hardware is actually doing. This means that we know exactly what the microcontroller is doing at all times since we are the ones manipulating the memory without much abstraction. This means with the proper development it would require much less instructions to run the same code in C than it would in higher level programming languages. The downside is that this makes software development much harder as we would have to work with harder concepts like using bitwise operators, dynamic memory allocation, and other lower-level programming methods. While our team has a good bit of experience programming in lower-level languages like C, because our image recognition software will be using Python, we would like to keep another higher-level language for our microcontroller if possible. The MSP430 also supports all of the common methods of communication methods such as UART, I2C, and SPI. This development board supports the use of both 5 volts as well as 3.3 volts. To program and debug this microcontroller it has a dedicated section of the board that has JTAG on it that can interface with the microcontroller as well as the other pieces of hardware.

3.5.4 MSP430G2553

The MSP430G2553 is another development board in the MSP430 series that is meant for low power processing. This system is a much lighter weight and cheaper than the competitor above with the FR6989. This microcontroller is again very similar to what we have studied as a team in embedded systems, but this board we have also used in another course with junior design and actually making a printed circuit board using it. This board can also be programmed using Code-Composer Studio since it is another TI branded product. This development board is driven by a 16 MHz clock just as the FR6989. The G2553 has 16 KB of flash memory with all of it being available to the programmer. There is .5 KB of RAM which is a very small amount, but it would still get what we need done as we wouldn’t be using a ton of RAM on our low processing unit. This development board has a 10-bit ADC which is about 4 times lower resolution than what is on the other development boards. This could limit our range of reading from analog signals which we plan on using to detect a break in a light sensor. This development board has 24 general purpose input/output pins to be used for different features. This board also supports the major communication protocols like UART, I2C, and SPI just as the other boards. This development board comes with 2 real time timers with a 32 KHz clock speed. This has very similar pros and cons to the MSP430FR6989. This version is a bit cheaper with a slightly smaller number of features so this can still be a good candidate for testing and use of its microprocessor in the final design.

3.5.5 ESP32-DevKitC

The ESP32 is a different series of low-cost and low-power system on chip microcontrollers that has integrated Wi-Fi and Bluetooth. Having Wi-Fi and Bluetooth, while not super pertinent in our final design not requiring any wireless connection, may have a good benefit when trying to test and properly design our system. The ESP32-DevKitC comes with a hardware reset button on the module and a boot button that allows for firmware downloading. It comes with a USB to UART Bridge for writing code to the board through USB making it easy to flash a new program onto the board which is a big requirement for easy testing of the system. This development board comes with 39 different general-purpose input/output pins. The ESP32 has 448 KB of ROM for booting, 520 KB of SRAM. This board uses a 40 MHz to drive the CPU which is faster than the other boards that we are comparing. This board also supports major communication methods such as UART, I2C, SPI, Wi-Fi, and Bluetooth. This board comes with a lot of new features on it that would help for debugging purposes, however the datasheet comes saying that it is not recommended for new designs. This is because there are newer products that come with more features even though this board is still in production. We are designing a new product so we do not want any of our hardware to be deprecated in any way, this means that we are not allowing the ESP32-DevKitC in our final comparison of development boards that we will be using to test our designs.

3.5.6 Development Board Choice

Between all of these different development boards a lot of them have very similar features for what we are needing. Since this development board will also influence what microprocessor, we choose to go on our PCB this is an important choice to be made. Below we have a table summarizing the different development boards along with some of their main features that we are choosing to look out for.

Table 3.5.6.1 Development Board Comparison

| Device | Flash | RAM | GPIO Pins | Programming Language | Price |
|-------------------|--------|-------|-----------|----------------------|-------------|
| Arduino Mega 2560 | 256 KB | 8 KB | 54 | Arduino IDE | Already Own |
| Arduino Uno | 32 KB | 2 KB | 14 | Arduino IDE | Already Own |
| MSP430FR6989 | 128 KB | 2 KB | 83 | C | \$26.59 |
| MSP430G2553 | 16 KB | .5 KB | 24 | C | \$12.00 |

After careful consideration of the table above we have decided to move forward with the Arduino Mega 2560. This comes with some very great features that will help us test and debug as well as it will make programming a lot easier. The high level of abstraction will allow us to development software without much need or worry of our low-level memory accesses. This has large amounts of overkill when it comes to read and write memory as well as the number of general-purpose pins on the board which is a great feature to have when testing this way, we can determine how many

pins will be needed in the final product. This is much better than having a development board with too little, then having to upgrade it to something with a larger amount. One of the most redeeming features of using this board for testing is that we already own this board so there will be no need to buy an extra component that will be used purely for testing that will not go into the final product.

3.6 PCB Components

The BIRDS brain and central management unit will be a printed circuit board that will interact with the peripheral devices, such as the capacitive sensor, laser break sensor, and all the actuators directly and coordinate with the image processing computer. For this, the PCB will require a dedicated microcontroller unit to process and run the required code.

3.6.1 Microcontroller Unit

We decided to use the same family of microcontrollers as the Arduino boards because of their compatibility with the grand included libraries of Arduino and because we already own an Arduino Mega 2560, which should make the transition from the prototype to the PCB easier.

Table 3.5.1.1. 8-bit Atmel Microcontroller Comparison

| Device | Flash | EEPROM | RAM | I/O Pins | 16-bit resolution PWM channels | Serial USARTs | ADC Channels | Price |
|------------|-------|--------|-----|----------|--------------------------------|---------------|--------------|--------|
| ATmega640 | 64KB | 4KB | 8KB | 86 | 12 | 4 | 16 | \$5.7 |
| ATmega1280 | 128KB | 4KB | 8KB | 86 | 12 | 4 | 16 | \$16.2 |
| ATmega1281 | 128KB | 4KB | 8KB | 54 | 6 | 2 | 8 | \$13.6 |
| ATmega2560 | 256KB | 4KB | 8KB | 86 | 12 | 4 | 16 | N/A |
| ATmega2561 | 256KB | 4KB | 8KB | 54 | 6 | 2 | 8 | \$25.4 |

Datasheet Atmel. Appendix B

Out of these microcontroller options, the ATmega1281 fits our proposes well. It is most definitely overkill for what we require, but it is easier to have leftovers than to lack flexibility.

3.6.2 External Communications

The relevant purposes for communication with foreign entities is if we implement a log system that records a list of activities with possibly a snapshot from the cameras and to notify someone when food or trash are empty or full respectively. However, the trash and food notification system would require additional sensors which is a stretch goal that most likely won't be realized.

3.6.2.1 Bluetooth

3.6.2.2 Data Port

Since we only want to implement logging system with camera snapshots, it would be much easier to connect directly to a built in USB port to the image processing unit.

3.6.3 Board Programing Port

The development boards have everything on it allowing the user to go straight from programming to automatically writing to the flash memory through just a USB. The microcontroller itself does not have such a feature. In order to write memory for the microcontroller to read from, there needs to be some kind of communication protocol to write to it. The ATmega1280 that we are using has a few different ways of being able to flash the memory to write the program to it. In these upcoming sections we will talk about some of the benefits of using one over the other and decide which will best suit our needs.

3.6.4.1 Parallel Programming

The Parallel Programmer is the most complex of the three with 16 different connections not including any power connectors or ground. This method is unique in the fact that it uses a 12-volt pulse to start the programming. This has the benefit of being able to program the fuses as well as the flash memory. The biggest strength of using the Parallel Programmer is that it can overcome any issue with any of its fuse that may come up later on. An example of one of these issues could be caused by programming a reset fuse bit to the incorrect value. This would cause the device to stop working and then render it completely useless as a microcontroller. That is just one example of how a software bug can cause something like that to happen, but there is many more that could also occur. A parallel programmer is essentially a key to any software lock that may occur. This interfacing method is great for fixing problems, however it is not practical when it comes to just programming the board. Because of the issue of practicality this will not be implemented into our board and will be left as a tool for possible connections later.

3.6.4.2 Serial Downloading

Serial Downloading is the simplest of the 3 interfaces as it just uses serial data to write to the flash memory. This is included in the ATmega1280 as it has something named ICSP which stands for in circuit serial programming. This is just taking information and writing it through an SPI interface to the microcontroller flash memory. In using this method, we would use the Arduino development pack that could connect to the circuit board. This would use another board that has the capability to transmit data through a serial connection. The Arduino IDE allows for direct programming of taking a specific program and writing serially to a certain microcontroller. This would then require a 6-pin connection header that we can connect to the Arduino Mega.

While using another Arduino would be very easy to setup, it can be very prone to error. Instead of using an Arduino, a product such as the Atmel ICE is an alternative that gives the same thing but is less prone to error. This device is not very cheap starting at \$200 which is unreasonable for what we plan on using it for. There is another device that is called the AVR ISP Mk2 that does a very similar thing at much more reasonable prices starting around \$20. Going with this option provides us the ability to program the microcontroller in circuit very easily by just connecting USB to the device and the device to the 6-pin header properly routed.

3.6.4.4 JTAG

JTAG is a great debugging interface that stands for Joint Test Action Group. JTAG is mainly used for programming and debugging for microcontrollers. JTAG is best used for more complex systems as it can be connected to many different devices in a daisy-chain fashion helping to test many systems at once. JTAG allows for hardware breakpoints throughout code giving more power to the debugger. This would significantly speed up software development for the microcontroller because having breakpoints like this cut down on the bug fixing part of programming by a significant margin.

3.6.4.5 Programming Port Conclusion

For our application, it makes the most sense to go with something that allows us to program in a reasonable amount of time in a simple way. What is nice about all of these options is that they can all be available later to choose from if we need to change for any reason. We plan on using the serial downloading method. This method seems to be widely used for projects such as these with little overhead and easy adapters to connect to. The parallel programmer will be a good fallback should we ever need to reset certain fuses because of any sort of program that goes wrong in production.

3.7 Power Circuit

To power all the systems for the BIRDS, we will need a power system able to supply operations for at least a week. Now calculation how much capacity we will need is a challenge, because since we don't have a prototype, we can not test power draw for normal operations. This is why the capacity amount of the batteries might be one of the last things we decide on. However, we can still choose and compare battery technologies. In addition to battery power, the nature of where a BIRDS might be located (out in the open, probably under direct sunlight), it might be fun and useful to implement some type of solar charging system.

3.7.1 Battery Power

Since we want autonomous operations, we will need some type of battery technology to supply the power when isolated. The battery will supply small amounts of power when in sleep mode (from the capacitive sensor) and large amounts of power when running the image recognition software. Not to mention the solar cells that may charge the batteries when in sleep mode. Our chosen battery will have to be able to constantly deliver power and be able to recharge while in use.

3.7.1.1 Lithium Ion Battery

“Lithium-ion (Li-ion) batteries are rechargeable power sources found in a wide range of portable devices, including smartphones, laptops, and electric vehicles. The fundamental operation of these batteries relies on the movement of lithium ions between two critical components within the battery structure. Here's a simplified breakdown of how lithium-ion batteries work:

A typical Li-ion battery comprises three key elements: a positive electrode (cathode) made of a lithium-based compound, a negative electrode (anode) usually composed of carbon (graphite), and an electrolyte solution containing a lithium salt in a solvent. The interplay of these components is central to the battery's functioning.

During the charging process, an external voltage source, like a charger, applies a voltage across the battery's terminals. This voltage drives lithium ions from the cathode to the anode, where they become embedded within the carbon structure of the anode, effectively storing electrical energy.

In contrast, during discharge, when the battery powers a device, the stored lithium ions begin their journey back to the cathode through the electrolyte. This movement of lithium ions generates an electric current, which is harnessed to operate the device. The movement of ions is closely associated with the flow of electrons in the external circuit, resulting in the production of electrical energy.

The transfer of lithium ions between the cathode and anode is facilitated by chemical reactions at the electrode surfaces. These reactions involve the exchange of electrons, and they are entirely reversible, enabling the battery to be charged and discharged repeatedly.”²³

It is easy to see how Li-ion came to dominate personal electric devices with their impressive energy density and ability to recharge. However, for safe use, Li-ion batteries require some type of management system that protect it from overcharging and overcurrent, especially if using multiple Li-ion packs. For the BIRDS, it is a good fit for all the reasons above. We will only need to implement some type of battery management system or buy a battery pack with it included.

3.7.1.2 Lithium-Polymer Battery

“Lithium-polymer (LiPo) batteries, like their lithium-ion counterparts, are rechargeable power sources found in numerous electronic devices, particularly in applications where a flat and lightweight design is essential. The operational principles of LiPo batteries share commonalities with lithium-ion batteries, yet they exhibit distinctive characteristics. Here's an overview of how LiPo batteries function:

LiPo batteries are constructed with multiple layers of a flexible, porous polymer separator embedded with an electrolyte. These layers encompass positive and negative electrodes, with the positive electrode often containing lithium cobalt oxide (LiCoO₂) and the negative electrode frequently including graphite.

What sets LiPo batteries apart is their utilization of a solid or gel-like electrolyte as opposed to the liquid electrolyte found in conventional lithium-ion batteries. This polymer-based electrolyte not only enhances safety by reducing the risk of leakage but also allows for a pliable packaging approach.

The operation of LiPo batteries revolves around the movement of lithium ions within the solid or gel-like electrolyte. During charging, an external power source applies voltage across the battery's terminals. This voltage initiates the migration of lithium ions from the positive electrode (cathode) to the negative electrode (anode) via the polymer electrolyte. The energy is stored in the form of chemical potential.

Subsequently, when the battery is employed to power a device, the lithium ions undertake a return journey from the anode to the cathode via the solid or gel-like electrolyte. In this process, the stored energy is liberated, generating an electric current that powers the device.”²⁴

²³ [GPT – Component Research -Ans8] Lithium-Ion Description by ChatGPT

²⁴ [GPT – Component Research -Ans10] Lithium Polymer Description by ChatGPT

While the increased flexibility and lighter batteries are interesting, the increase in price does not justify the minute differences of LiPo batteries over Li-ion.

3.7.1.3 Nickel-Metal Hydride Battery

“Nickel-Metal Hydride (NiMH) batteries are rechargeable power sources widely utilized in various consumer electronics like cordless phones, digital cameras, and handheld tools. These batteries operate by enabling the movement of electrically charged ions within their structure. Here's a simplified account of how NiMH batteries work:

A standard NiMH battery consists of three primary constituents: a positive electrode known as the cathode, which is made from a compound containing nickel oxyhydroxide (NiOOH); a negative electrode, referred to as the anode, composed of a hydrogen-absorbing alloy, often featuring a blend of metals including rare earth metals and nickel; and an electrolyte, typically a potassium hydroxide (KOH) solution that facilitates the flow of ions between the anode and cathode.

During the charging process, when you connect a NiMH battery to an external voltage source, like a charger, a voltage is applied across the battery terminals. This voltage prompts the oxidation of nickel ions (Ni^{2+}) from the cathode, resulting in the formation of nickel oxide (NiOOH). Concurrently, hydrogen ions (H^+) are liberated at the anode.

When the battery is deployed to power a device, the inverse of the charging process unfolds. Hydrogen ions (H^+) at the anode engage with the metal hydride alloy, leading to the release of electrons, thus generating an electric current. Meanwhile, nickel oxide at the cathode accepts electrons and releases nickel ions (Ni^{2+}).

Throughout both charging and discharging phases, charged ions, encompassing nickel ions and hydrogen ions, journey back and forth between the anode and cathode via the electrolyte. This reciprocal ion movement is the basis for storing and discharging electrical energy.

The beauty of NiMH batteries lies in their ability to recharge and discharge multiple times owing to the reversibility of chemical reactions occurring at the anode and cathode. NiMH batteries typically provide 1.2 volts per cell, which is slightly lower than the 1.5 volts of alkaline batteries, yet they compensate for this with higher capacity and the reusability factor. It's worth noting that NiMH batteries experience somewhat higher self-discharge rates compared to some other rechargeable batteries, which implies they may gradually lose stored energy over time, even when not in active use. Regular full discharge and recharge cycles help maintain their performance and longevity.”²⁵

While NiMH batteries might be safer to use, they lack the energy density of lithium batteries. I doubt the BIRDS will run on AAA batteries.

3.7.1.4 Lead-Acid Battery

From its name, lead-acid battery creates power by submerging lead into some type of acid, most often sulfuric acid.

“Lead-acid batteries, known for their durability and long history of use, are prominent as rechargeable energy storage devices in various applications, including vehicles and uninterruptible power supplies. The core of a lead-acid battery's operation hinges on electrochemical reactions

²⁵ [GPT – Component Research -Ans12] Nickle-Metal Hydride Description by ChatGPT

taking place between lead dioxide (PbO_2) and sponge lead (Pb) immersed in a sulfuric acid (H_2SO_4) electrolyte. Here's a simplified elucidation of how lead-acid batteries function:

A standard lead-acid battery is composed of crucial components, including the positive plate (made of lead dioxide), the negative plate (consisting of sponge lead), a separator to prevent short-circuits between these plates, and the electrolyte, a dilute sulfuric acid solution that enables ion flow between the plates.

During discharge, when the battery is employed to power a device, the lead dioxide at the positive plate (anode) reacts with the sulfuric acid (H_2SO_4) in the electrolyte, leading to the formation of lead sulfate (PbSO_4) at the positive plate. Simultaneously, electrons are released at the anode, setting in motion an electric current that provides power to the connected device.

Conversely, when the battery is being charged, a reverse chemical process unfolds. Lead sulfate at the positive plate undergoes conversion back into lead dioxide, while sulfuric acid is regenerated in the electrolyte. During this operation, electrons are consumed, effectively reversing the direction of the electric current. Electrons flow from the negative plate (cathode) to the positive plate via an external circuit, constituting the electrical energy.

In both the charging and discharging phases, sulfate ions (SO_4^{2-}) traverse between the plates through the electrolyte, ensuring a balanced electrochemical environment.”²⁶

Since the chemicals are always in contact, slow degradation of charge happens constantly and eventually the battery needs to be replaced. This, plus the severe limit on battery drain to prevent battery damage, makes Lead-acid batteries unsuitable for the BIRDS.

3.7.2 Wired Power Supply

Worst case scenario is that we are unable to implement a battery system and, therefore, would need to use a wired power supply. It would break the goal for autonomous operation, but the BIRDS would continue to work.

This would be a simple implementation. Just add a barrel jack that connects to a 9V power adapter and design a power regulation system to step it down.

3.7.3 Voltage Regulators

If we decide to implement battery packs with voltages higher than the operating voltage for the MCU and peripheral devices, we will need to implement voltage regulators to step down power source voltage.

3.7.3.1 Buck Converters

“A buck converter, also known as a step-down converter, is a type of DC-DC power converter widely used to efficiently reduce a higher input voltage to a lower output voltage.

The buck converter consists of several key components: an input voltage (V_{in}), a semiconductor switch (usually a MOSFET), an inductor (L), a diode (D), and an output capacitor (C). When the switch is closed, current flows from the input source through the inductor into the load, storing energy in the inductor. During this phase, the diode blocks the current. When the switch is opened,

²⁶ [GPT – Component Research -Ans14] Lead-Acid Description by ChatGPT

the inductor releases its stored energy, transferring it to the output capacitor and load, with the diode allowing this energy flow.

This switching process occurs rapidly at a controlled frequency, thanks to pulse-width modulation (PWM). By adjusting the duty cycle (the time the switch is on relative to the total switching period), the output voltage can be precisely regulated.”²⁷

Probably the most widely used and efficient DC-DC step down converter. Compared to other ways to step down voltage such as, a simple voltage divider or the similar Low Dropout Regulator, the buck converter does not rely on simply burning off excess power. Instead, it stores and regulates power through magnetic and electric fields. If the need for a step-down converter arises, we most definitely will implement a buck converter.

3.7.3.2 Boost Converters

“A boost converter, also referred to as a step-up converter, is a type of DC-DC power conversion device with the primary function of raising a lower input voltage to a higher desired output voltage.

The essential components of a boost converter include an input voltage (V_{in}), a semiconductor switch (usually a MOSFET) responsible for controlling current flow, an inductor (L), a diode (D), and an output capacitor (C). When the switch is closed, current flows from the input source through the inductor, and this phase results in the storage of energy in the inductor. Simultaneously, the diode blocks current flow in the reverse direction.

When the switch is opened, the stored energy in the inductor is released. What distinguishes the boost converter is the way in which this energy is transferred to the output. Rather than simply passing it along, the boost converter adds this energy to the input voltage, consequently increasing the output voltage.

The operation of a boost converter is managed through pulse-width modulation (PWM), where the duty cycle of the switch is adjusted to control the output voltage level.”²⁸

Closely related to Buck Converters, Boost Converters are the only decent way to step up voltage. And just like with Buck Converters, we will make use of Boost Converters in the BIRDS

3.7.3.3 Low Dropout Regulators

“Low Dropout Regulators (LDOs) are essential electronic components used to ensure a stable and precise output voltage, even when the input voltage is only slightly higher than the desired output voltage. They play a crucial role in various electronic devices, providing a reliable power supply for sensitive components like microcontrollers, sensors, and RF circuits. Here's a closer look at how LDOs work

At the core of an LDO is the pass transistor, typically a MOSFET, which serves as a valve controlling the flow of current from the input voltage to the output. The key challenge for LDOs is to maintain a stable output voltage when the input voltage drops, and this is where their low dropout feature comes into play.

LDOs employ a feedback mechanism to continuously monitor and adjust the output voltage. They have an internal voltage reference, often implemented as a bandgap voltage reference, that

²⁷ [GPT – Power Circuits – Ans 2] Buck Converter Description by ChatGPT

²⁸ [GPT – Power Circuits – Ans 4] Boost Converter Description by ChatGPT

establishes the desired output voltage level. An error amplifier continuously compares the actual output voltage with the reference voltage. When any deviation is detected, the error amplifier generates an error signal.

This error signal guides the pass transistor's operation. If the output voltage falls below the desired level, the pass transistor opens up, allowing more current to flow and thus increasing the output voltage. Conversely, when the output voltage exceeds the desired level, the pass transistor reduces current flow to lower the output voltage. This continuous feedback loop ensures that the output voltage remains regulated, even when the input voltage is close to the output voltage.

To further stabilize the output voltage and reduce voltage fluctuations, LDOs are often equipped with an output capacitor. This capacitor helps mitigate transient voltage changes and provides additional filtering to ensure a clean and steady power supply.”²⁹

While not as efficient as Buck converters, LODs can serve a critical role in providing stable voltage. If we are to implement some type of self changing, such as solar cells, receiving a constant and reliable voltage would be critical. We would use LODs for smoothing out small fluctuations of solar power, in addition to its dedicated solar power management system.

3.7.4 Solar Cells

“Solar cells are typically made from semiconductor materials, with crystalline silicon being the most common choice. When sunlight, which consists of tiny packets of energy called photons, strikes the surface of a solar cell, some of these photons are absorbed by the semiconductor material. This energy absorption excites electrons in the semiconductor, causing them to jump from a lower energy state to a higher one.

The semiconductor material in solar cells is specially designed with a p-n junction. The p-side is doped with materials that create an excess of positive "holes," while the n-side is doped to have an excess of electrons. This difference in doping creates an electric field at the junction. When the excited electrons and "holes" are generated, the electric field in the cell separates them. Electrons are pushed toward the n-side, while holes are pushed toward the p-side. This separation of charges results in the generation of an electric current.

Metal contacts on the surface of the solar cell collect the liberated electrons and facilitate their transfer to an external circuit. The flow of electrons in the external circuit creates electric current, which can be harnessed to power various electrical devices, charge batteries, or be fed into the grid for broader use.”³⁰

If we want to implement a solar charging system we will require power converters to collect, convert, and provide a smooth voltage to either charge the battery or power the sleep mode of the BIRDS. However, implementing a power supply system that switches from different sources might be more challenging than continuously changing the battery.

3.8 Part Selection Summary

So far we have picked out a few technologies:

Our actuators will use Servo motors to drive the trash sorter.

²⁹ [GPT – Power Circuits – Ans 5] Low Dropout Regulator Description by ChatGPT

³⁰ [GPT – Power Circuits – Ans 6] Solar Cell Description by ChatGPT

The main PCB will be powered by an ATmega1281 microcontroller.

Supplementary visual stimulation will be provided by LEDs and auditory stimulation by a buzzer.

The battery will most likely be a lithium-ion battery.

4. Standards and Design Constraints

4.1 Standards

Standards are an inescapable fact of life that everyone has to deal with at all times. Standards can appear in the clothes we wear on our back all the way to the electronics we use. It is important that we follow these standards so that we can keep everything in place. To keep our project in high regard, we have to make sure that our project can stay inside of these standards. It is important to be aware of these set of standards, so in the following sections we will be listing some of these standards in which we will be abiding by.

4.1.1 Electrical Safety

Our products involve electronic systems, so this means that we have to abide by the UL67 standard. The UL67 standard is a standard for making sure that the cover panelboard for the electronics is properly used with the primary function of control and protection of electrical circuits. We need to make sure that all of our electrical circuits are blocked so that no accidental contact can be made. The UL67 standard is not only applicable to high-power applications, but it also applies to any electrical enclosure regardless of power distribution. We must make sure that even though our system is a low power system we abide by these regulations.

To follow in accordance with this electrical standard we will be taking the following steps. We will make sure that all of the electronics are in an individual box cover so that no accidental exposure to live electrical components can happen. This includes but is not limited to our printed circuit board, our image processing system the Jetson Nano, and any connections to external sensors or devices. This box needs to be extremely tamper proof on the off chance that any animal could possibly encounter it. We are building the outer housing to be tamper proof, but on the off chance that somehow an animal gets through that, there needs to be no chance that any live electronics could be touched by them. Not only animals might be able to come in contact with these components, but also people who are performing maintenance on any of the physical systems as well. So, this box needs to be clearly labeled and marked so that no accidental touches can be made.

4.1.2 Environmental Standards

Our device will be working with birds, meaning that our device must also meet certain environmental safety standards. The main intention is to deploy this outdoors, meaning that our housing must be weatherproof enough to survive the elements. This means that we need to make sure that our housing we choose has a high enough IP rating to survive the constant stream of different elements that it may run into.

In an IP rating there is 2 numbers that represent the protection that it provides. The first number is for solid particle protection. This is for protection against things like dust, dirt, or something bigger like tools and wires. This scale goes from 0 all the way up to 6 where 0 is the least effective and has no protection against contact and ingress of objects, where 6 represents being dust-tight where

no ingress of dust. The second digit is for protection against liquids. This scale ranges from 0 to 9K. In this scale 0 is the lowest with it being effective against no form of water, where as 9K represents protection against powerful high-temperature water jets. There are also some extra letters that can be added on to add some levels of detail. These additional letters are as follows. For protection against oil the letter f is added. For protection against high voltage the letter H is added. M is for monitoring during water test, S is for standing still during water test, and finally W is for weather conditions.

For our system a reasonable IP would be IP64 which means that it is completely dust and dirt resistant and that it can resist water splashing from any direction. This would be a good choice because the system being outside it will be windy and often times dirt and dust will get kicked up. Not only that but the times that it rains it will be windy with water downpouring meaning that we will want water protection from all angles.

4.1.3 IEC 61215

The IEC 61215 standard is on design qualification and type approval for terrestrial photovoltaic modules. This is essentially how to implement solar panels into a design. This includes indoor and outdoor designs in open air. This standard defines qualification tests that modules should undergo to verify their durability in different environments. This means that the panels have also been tested in different environments and can withstand things without significant degradation. In order to use solar panels that can hold up in the environment we need to make sure that the solar panels we use have gone through testing to meet this standard.

4.1.4 Battery Standards

In our choice of battery, we need to make sure that it can meet all standards on batteries appropriately to be able to incorporate in our design. Our plan is to use a lithium-ion battery in our design to be able to meet our constraints. The IEEE 1625 is a standard relating to the design and manufacture of these lithium-ion batteries. To make sure that we have proper batteries that comply to these standards we must make sure that they are rated as such.

4.2 Design Constraints

Our team must be able to balance between feature of development as well as cost of the components and boards. It is very common that the more expensive option has enough more processing power, but it increases heavily with its cost. For our system we need to have something that meets all of our design philosophies without giving up too much in any one particular field. In the upcoming sections we will discuss some of the different constraints that we decided how we are going to approach as well as some problems that may arise.

4.2.1 Economic Constraints

In designing our system, a big factor to take into consideration is the economic constraints. As we are in college we would like to spend as little money on this as possible while trying to keep all of our requirements met. Luckily, we do have a sponsor for this project that will be supporting us as we pick out devices and electronics for developing. Because we have a sponsor for the project that also means that we need to keep our project within budget, or we will have to start paying for things out of pocket. Even with a sponsor we want to try to keep options as affordable as possible so that this project would be reasonably priced if it went to market. This means we need to make

sure that we spend enough time in the researching phase to guarantee that we can stay under our budget requirement while also meeting the specification requirements. This is sometimes known as getting the most bang for its buck, basically meaning you are getting performance for every dollar. Keeping all of these things in mind as we move along will be pertinent to make sure that we meet our goals without upsetting our sponsor or having to spend too much money ourselves.

4.2.2 Time Constraints

The time constraints put upon us are probably among the most stressful for this project. Because this is our senior design project in the course, we need to make sure that all of our goals are met on time. Failure to do so can result in one or all of us retaking senior design from the start again. This would severely delay our graduation. In order to make sure that this doesn't happen we as a team need to ensure that we have a working prototype by the end of senior design 1 and the device is working and fully functional by the end of senior design 2. This only leaves us with about 4 months to get a working prototype and then another 4 months to get it fully functional. This on top of other classes will be one of the hardest constraints to follow, but also the most important. There are some things that might become a hurdle in meeting this time constraint that we will discuss further.

One of the main hurdles that our group will most likely run into is with the printed circuit board design. No one in our group has any real experience with this kind of work so this will be starting from scratch for all of us. First, we need to make sure that we have all of our components picked out and they all properly work together. This adds some extra delay to actually designing our PCB because we don't yet know what components to include in our design. Then finally after the PCB is designed in software, we then need to wait for it to actually be manufactured. This process can typically take anywhere from 3-15 business days. All of this time adds up and this is still before we even have the board to test in our possession. After receiving it there will definitely be things that don't work the first time, meaning there will be fixing of the board. This will involve desoldering and resoldering items on to it which add to development time. Because of all of this information, we need to make sure that we order our PCB with time to spare to meet the requirement for time.

Another section that can affect time it takes to develop is the fact that some of our team members live a bit far away from campus. This means that meeting up can sometimes be a bit hard to coordinate as the commute just takes too long. Not only the commute but many of us have jobs or internships that we also have to try to balance along with the commute. This makes in person meetings very hard and generally can only happen around once a week with our very busy schedules. We are fortunate enough to be able to use things that allow us to meet online named Discord. We will discuss Discord further later in the paper.

4.2.3 Environmental Constraints

As mentioned, the potential environmental impact our project could create, as it will be interacting with birds and potentially other animals, gives significant reason for environmental safety precautions. This means we need to consider our surroundings and make sure that our device is as economically friendly as possible. On the flip side we still need to make sure that all of our specifications are being met while keeping this goal true. We can not afford to give up too much while trying to be economically friendly. One of the best ways we plan on keeping this environmentally friendly is through the use of solar panels. These solar panels will be hooked up to our rechargeable battery. This means that it is using renewable energy in order to give the battery

extra charge and longer battery life. This limits us with the placement of the system. We need to make sure that our system when placed has easy and plentiful access to sunlight to make sure that it is being charged adequately.

While keeping a battery charged through the use of solar is great and helps limit the use of charging the battery through other means, this isn't the only thing that we need to worry about. We need to ensure that no wildlife can be harmed from our system at all. To do this we need to think about the kind of food that the system should be filled with, the possible noises that it may make, and just any possibilities of malfunctions that may potentially arise in the future with no one around to fix right away. One way of helping with this is by keeping the system closed until a bird comes, this way no other animals have the possibility of getting trapped in any sort of housing or having something closed on top of them. We also need to make sure that any LEDs that we add or any noises that may play for positive reinforcement are not at all detrimental to any kind of animals that may approach our system.

In keeping all these things in mind this allows our placement of BIRDS to be more versatile and thus covering more ground. Keeping the environment safe is a very important task for us considering that we are building something that can be used to help clean the environment. If this were to create more waste than it does help it would render our project useless. This also makes our project more marketable as we can be presenting a topic that can help the environment as well as clean up the world.

4.2.4 Social and Political Constraints

The main objective of BIRDS is to provide a service in which to train birds by. This system will mainly be for the use of people who are willing to train the birds. This will act as a helper to their training as they will need to introduce them to the system first. This means that we will be aiming towards bird trainers with our product. Once one or two birds are trained it will spread to more birds realizing what is happening and then more birds will begin to come to exchange trash for food. While this product could very much go to the general population as a product, the intention is more so for the use of cleaning up particular areas that birds can access. This means that we need to aim to please bird trainers in the way the system works in order to properly meet the goals that we are shooting for. We want this device to be easy to install as well as easy to handle and access. The reason for this is that we do not intend for people who are well versed in electronics to be handling this device. We want to make it as user friendly as possible so that it does not matter who buys and uses this device, even if they may have no idea how the electronics work.

As for political constraints that we must abide by, not too many come to mind. The only real thought we had that could cause some political problems could be if the device is placed in a location where birds should not be fed. This does not have too much impact on our design. As a team we have decided as long as everything is up to standard, and we do not use anything that could possibly be illegal in any way then this constraint poses no threat to our project.

4.2.5 Ethical Constraints

As we develop our project further and progress in our research, we plan on keeping our standards of safety very high. We need to always keep this in mind as we will be making a system that will not only be useable by people but also by birds. This makes the talk of ethics come very largely into play as these birds will be interacting with our system and we need to make sure that we do not put them in any sort of danger or cause stress or harm to any of these animals. These sorts of

conversations have come up already in our research when we were discussing the design of how the bird would deposit trash in the first place. Our original thought was to have a housing that is closed off to all other animals and to open up only for a bird and allow the bird inside of the house. With great intentions we had planned on birds coming inside to drop off trash. This introduces a lot of extra variables and things to worry about. Now the question becomes what precautions we can take to make sure that no bird gets stuck or harmed inside of our housing. This is why we changed the design to only open a portion that the bird can drop things inside rather than having an entire location for them to come inside. If we were to allow birds inside, we would need to add so many extra layers of precautions to absolutely ensure that no bird could ever nest inside, or potentially unwillingly get stuck inside. This was one of our first steps to ensuring that our project stays ethical with no risk to any people or birds that may come into contact with our system.

Another very important aspect, on the topic of ethics, is the material that we make our device out of. There will of course be the need of protective layers inside to house the electronics away from reach of any animal or accidental contact. This box needs to be strong enough so that no animal could slip through and try to chew on or even eat any electronics. This is very important as wild animals will not know what it is they are trying to get to, but they will try anyway as their curiosity will get the better of them. The first way of properly making sure that this does not happen is to make sure the outer housing cannot be penetrated in anyway and is safe to animals. This means that there should not be any sharp edges or possible material that could harm the ecosystem or any animal to come into contact. This means that we will have to make sure that all of our corners are rounded and there is no possibility of anyone getting hurt. This should also be material that is sturdy enough to withstand any battering of an animal that might try to break inside. The source of the material is also important. This material can not be anything that may be detrimental to the animal's environment. This could be anything from the color to the scent of the material. All these things are important to take into consideration when we are making a product designed for the purpose of working with animals.

4.2.6 Manufacturing Constraints

Another set of constraints will be placed on the production and manufacturing of the BIRDS, specifically the physical housing and waterproofing and the mechanical parts of the system. There will be limitations on what can be done when building and the materials that can be used for the exterior housing, for example, based on our desires for the system to be lightweight, durable, and waterproof. The construction of our system will also be heavily dependent on the building skills and resources we have. A lack of experience in typical manufacturing procedures like soldering or 3D printing would cause a fairly significant constraint on the structures we can produce. These limitations, however, can be overcome with resources, whether those be other people who are more familiar with these manufacturing processes, or tutorial videos we might use to learn how to do them ourselves. Time and cost constraints will go hand in hand with these manufacturing constraints.

Another future manufacturing constraint to consider if the BIRDS is to be made available and produced as a commercial product down the line is the efficiency of production and ease of replication in building the system. If we even want to consider making the system readily available for campuses, governments, or other potential customers to use, making the system efficiently produced and manufactured in a way that makes it worth the time and cost, both for us in producing and for customers in purchasing, is another constraint to consider.

4.2.7 Sustainability Constraints

When the factors of environmental and animal hazards are considered, a high importance is placed upon the sustainability of our system. Since the BIRDS will be placed outside, where it will be exposed to the elements and to wildlife, efforts to give the system a suitable durability that will sustain it without frequent maintenance will prove to be important. Weatherproofing will need to be implemented on the surfaces of the housing for our optical and electronic components, since these components do not mix well with water or any type of excessive moisture. We will attempt to encase all of these non-weatherproof components inside of the housing to ensure they will not be susceptible to water or moisture damage. This, however, will impact and constrain various parts of our system's design, including where components will be able to be placed and how big sections of the housing will need to be. Though this may pose problems, there is a high importance placed on the sustainability of our system, given the goal of the system operating on its own for extended periods of time, possibly for a week at a time, without the manual maintenance of cleaning or drying. A robust and waterproof physical design will be a key part of the BIRDS.

Another significant reason for why the BIRDS will need to be robust is that it will be exposed to contact with wildlife. While the wildlife the system will come into contact with will mainly be birds that the system will be able to support without it moving too much or being damaged, other wildlife like squirrels or even cases where larger birds could compromise the integrity of the system need to be considered. A robust and weighted structure for the housing of the optics and electronics or the BIRDS will be necessary to protect against any threats against the sustainability of the system. This necessity will also pose constraints and important requirements for the design of the subsystems and their integration.

4.2.8 Health and Safety Constraints

When research for BIRDS, safety is our number one concern. Just as mentioned in our constraints for ethics we must make sure that our device is safe for all. This from the people who may do maintenance or change out any trash or food devices, all the way to the birds and any other animal that tries to use it. In order to ensure safety is preserved we will make sure to abide by the electrical standard of having all possible electronic contacts properly covered. This will guarantee that there is no accidental touches to any electronics by human and animal alike. We need to make sure that our materials all meet the correct standards to ensure no one is harmed in any situation.

To keep up with UL67 electrical standard, we must ensure that all devices and connections are covered appropriately. This is a little bit extra concerning with wild animals as there is much more possibility for contact unexpectedly. In a project working explicitly for humans it would be labeled as well as guarded. When working with birds, the labels will not go very far, and they will be more interested in getting inside. This means we will have to use extra sturdy material on the housing to guarantee that no animal can break inside. This will properly protect the electronics as a first line of defense. That being said it will still be important to clearly label anything for any human interaction with the system for maintenance or any other reason. We plan to have extra precautions should this outer housing ever be broken through or slipped between. This will include covering all electronics and wires together and making sure that no device, such as a camera or sensor, could possibly be eaten or interacted with by any animal in any way.

In keeping up safety the material of use is also of great importance. We must make sure that this material is properly sourced with no detriment to the environment whatsoever. This material must guarantee all animals safety, even if used in an unintended way. We must make sure that this can

properly hide away any potentially hazardous materials such as a lithium-ion battery. Having a battery in our design is without question as we plan on our device being able to run wirelessly in the wild. This means that there is not any way around such a component. With research we have found that lithium-ion batteries are generally safe and unlikely to fail. Due to this fact and that it is so widely used, we determined that this would be a good way to keep our health standard high as it is unlikely to fail. With that being said, if anything does go wrong with the battery if it gets damaged or fails to operate safely anymore it does pose a potential fire and explosion hazard. To make sure that we account for this, we will be making sure that the battery used is fully up to standard and high quality as this could be potentially very dangerous should we get the wrong device.

5. Hardware Design

5.1 Housing

5.1.1 Terminals

5.1.2 Storage

5.1.3 Internals

5.1.4 Externals

5.2 Analysis Chamber

This portion of the BIRDS will be located internally, collecting the trash that birds bring to the housing unit.

5.2.1 Imaging System

The components that make up the trash imaging system are the LED, the lens, and the CMOS sensor. The LED will illuminate a fallen object, the lens will capture and focus light, and the CMOS sensor will take a picture and send the data to the Jetson Nano for processing.

The LED will be a white light source to properly irradiate the trash that birds drop into the analysis chamber. It will be placed at a specific location in the chamber to best light up the object and not interfere with any other systems, specifically the photodiode in the laser sensor. To avoid crosstalk between the laser and LED, the LED will be placed below the photodiode.

Properly designing the lens system required knowledge of the Thin Lens Equation, shown in Equation 1, and the linear magnification relationship, shown in Equation 2.

$$\frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{f} \quad (1)$$

$$\frac{s_2}{s_1} = M \quad (2)$$

where s_1 and s_2 are the distances between the object and lens and the focal point and lens, respectively, and f and M are the focal point and magnification, respectively.

These equations had to be correctly integrated with the mechanical design of the analysis chamber to form a focused image onto the sensor. The chamber is a cylindrical-like shape with a height of H . The lens design we will implement into the chamber is a single plano-convex lens system with s_1 set at infinity and s_2 approximated to be the focal length. This design allows for plenty of space for the trash to fall into the chamber and to also install the laser sensor below the lens.

Moving forward with this design, the magnification of the lens system is a crucial component of the design to focus the best image possible onto the CMOS sensor. To determine the optimal magnification of the image, we had to consider the average size of the trash being imaged, the size of the CMOS sensor, and the height of our chamber. With these three values known, we were able to find the right focal length to design our lens.

Our main goal is to be able to properly determine if a cigarette has landed in the analysis chamber. The average length of a cigarette is 8cm long.³¹ The size of our CMOS sensor is 4mm x 3mm. The magnification of the lens system required to capture a complete image of the cigarette onto the sensor is $\frac{3mm}{8cm} = 0.0375$. The entire length of the lens system must be less than the height of the system:

$$s_1 + s_2 \leq H \quad (3)$$

Using Equation 2, $s_2 = 0.0375s_1$. Therefore, from Equation 3, $s_1 \leq H/(1 + M)$ and $s_2 = Ms_1$. Plugging the new values of s_1 and s_2 , we find $f = \#$. The lens we have selected has an effective focal length of 6mm, which gives us some room for error in our chamber design.

5.2.2 Laser Motion Sensor

Also within the waste analysis chamber is the object detection laser motion sensor. This design will utilize a red laser source, a potential system of mirrors, and a photodiode. The laser source will be used to create a laser grid from which, if broken by a falling object, will cause higher order functions within the BIRDS. The mirrors will be placed in specific locations around the chamber walls to reflect the laser beam at calculated angles to form a laser grid where every object that falls into the chamber must break this plane. This mirror system will eventually reflect the laser light onto a photodiode which will sense when an object breaks the created light path.

The goal of this motion sensor is to create a laser grid which any object that is dropped into the analysis chamber will break. To achieve this, the laser diodes, the mirrors, and the photodiodes must be positioned around the cylindrical-shaped chamber, all at the same height, to send, reflect, and capture the laser light. As seen in Figure 5.2.1, Figure 5.2.2, and Figure 5.2.3, the components will be placed so that when the laser is aligned, the light will be reflected anywhere from 7 to 13 times depending on the design chosen. Knowing typical cigarettes brought by birds will be anywhere from 4cm-8cm, we want to design a grid without any spaces larger than 4cm that would allow trash to fall undetected. To plan for even smaller trash brought by a bird, we will aim to design the largest spaces to be around 3cm.

³¹ Talhout, 2018

One method to cover significant area is simply reflecting the laser through the center of the circle over and over from the different mirrors. Solving for the constraint of the largest spacing to be about 3cm, we must understand how to calculate arc length. Arc length is typically defined by an angle from the center of the circle and the circle's radius:

$$s = r\theta \quad (4)$$

However, we will multiply Equation 4 by two (i.e., use the circle's diameter) in our case because we are dealing arc lengths defined by angles on the opposite side of the circle. Given we design the chamber with a diameter of 12cm, the maximum angle the laser can form at the mirrors is found solving for θ in Equation 4 with $\theta = 14.3^\circ$. To give some room for error and to create a more symmetrical grid, we designed the laser grid with $\theta = 13^\circ$. As shown in Figure 5.2.1, the laser will reflect off of 12 mirrors into a photodetector when aligned. The maximum distance of space without a laser is shown as 2.699cm, less than 3cm.

This design also minimizes the chances that a cigarette or some other trash falls without breaking the plane. The goal is to misread falling objects only 5% of the time. Other mechanical designs will be discussed as to ensure the trash does fall through the laser light. This could be created in the form of a bumper causing long objects to spin forcing a greater surface area, or an edge designed to feed trash into the center of the chamber.

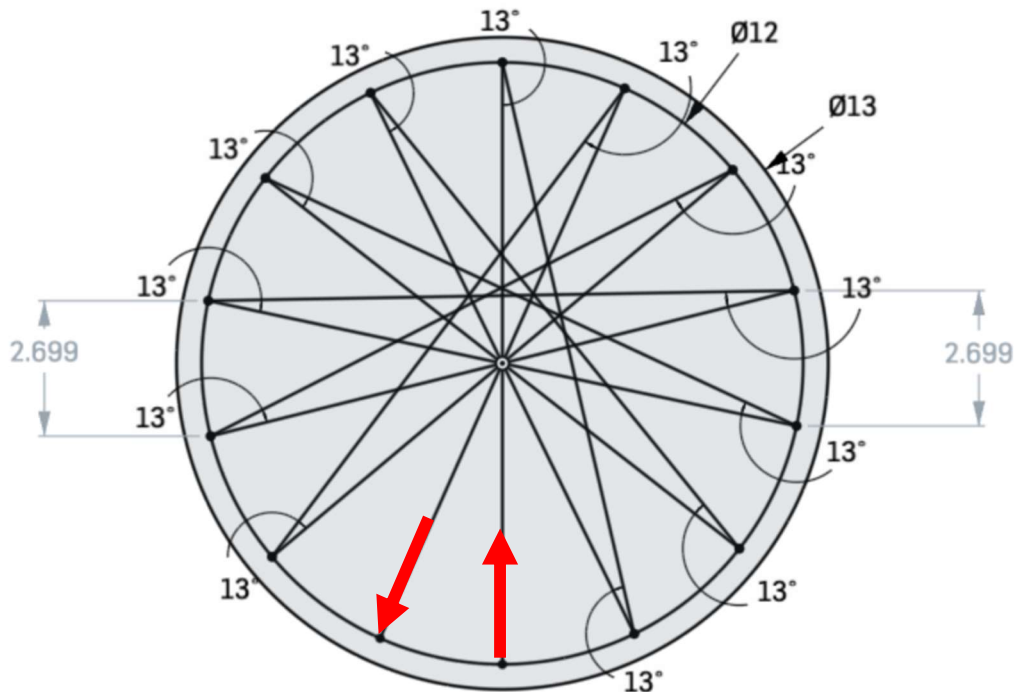


Figure 5.2.1 Laser Grid Design

A secondary design option for the laser grid would require multiple laser diodes and photodiodes. This method would form an actual grid-like structure with no mirrors used to maximize the surface area coverage.

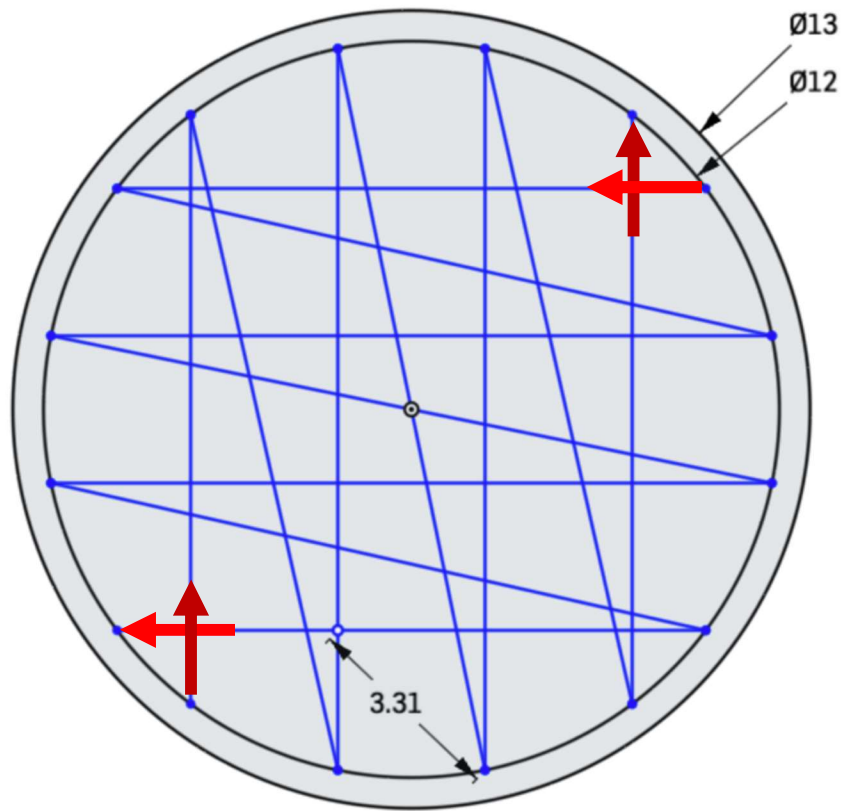
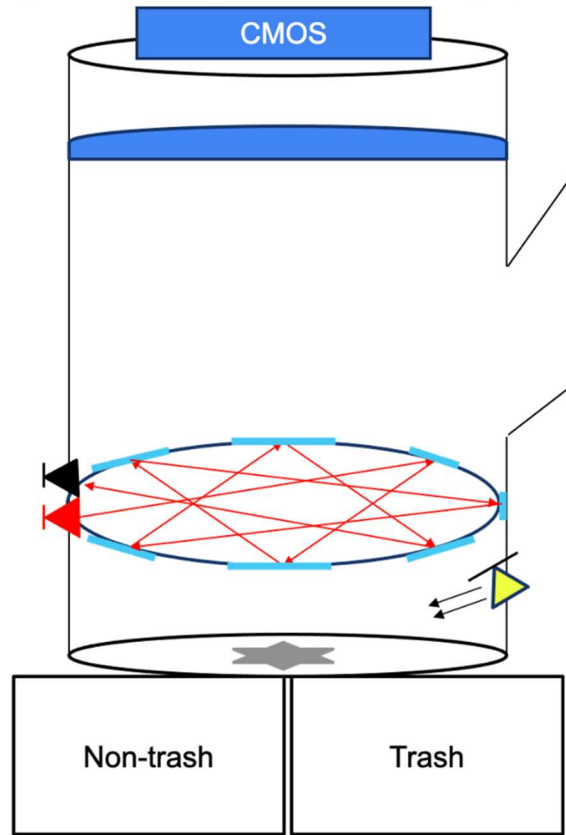


Figure 5.2.2 Integrated Trash Imaging System



5.3 Door Mechanism

6. Software Design

6.1 Philosophy of Software Design

In approaching software design there are many different methods to choose from that change how to go about solving a problem. These can change the entire paradigm of how our software design is tackled by our team. We will be discussing some different pros and cons of different design methodologies and how they will affect our team. This will be our chosen approach to stick with while we progress further into our design.

6.1.1 Agile

Agile is a development method that is used to minimize risk when adding any new functionality. In an Agile method teams develop software in iterations, which is just a small part of the project. These are almost like individual sections that will come together at a later stage. Each iteration is individually done then evaluated then to proceed to a further part of the project or to fix the current working iteration. This form of iteration software development is a big pro of Agile, as it allows teams to fix defects and properly align the expected outcomes early on in the development process.

The downside to Agile is that these iterations happen very regularly and quickly. This means that there needs to be real time communication when developing anything. This can sometimes be challenging as in order to finish an iteration the entire feature needs to be working as expected. This can range from taking a couple hours to maybe even weeks. This method is very good for rapid development, but it does make this a bit more labor intensive. There are some derivations of the Agile method that use the overall ideology, but with some twists. Some of these derivatives include Crystal Method, Dynamic Systems Development Model (DSDM), and Scrum. These are still mainly Agile methods but mostly for splitting chunks of projects into teams. Since we already are working with a small team, and an even smaller team working on software, these methods are not super useful among us.

6.1.2 Waterfall

The Waterfall method is a traditional software development approach. This method involves completely finishing a phase to 100 percent before moving on to the next. When this phase is done it can no longer be modified. This is a very rigid and linear approach but the most simple, as it splits things into phases to follow. This makes it very beneficial to a newer team in software development as we have a very clear path to follow. The biggest pro to this methodology is that it has very clear deadlines that everyone can know and follow. This not only makes the managerial role easier by setting the deadlines, but also makes everyone else's role easier that needs to follow a specific deadline. It is much easier to make sure that a product is completely ready for that specific deadline. The downside to this method is a very big pitfall of not being able to go back and correct or change any phase. This can be very detrimental during the integration part of our software development. During each phase individually it is great to work with one thing and make sure that it works perfectly, however during integration nothing ever works as expected. When things start to get added together, things never interact with each other as first expected.

6.1.3 Spiral

The Spiral methodology functions by continuously goes through a circular process throughout the lifespan of the project. The spiral being consistently traveled through includes Planning, Risk Analysis, Engineering, and ending with Evaluation. After this process is gone through once it starts back at the beginning of planning and travels through a new iteration of the spiral. Due to risk analysis happening very regularly, it is easy to handle something new with every single iteration through the spiral. This model improves communication since there is regular reviews throughout the spiral, as well as improving quality since there is multiple iterations through the spiral over and over. The downside of the spiral method is that it is very complex. This makes it harder to follow by the entire team since there is not as clear guidelines to what is going on. This model is good for large projects, which does not really suit our needs properly.

6.1.4 DevOps

DevOps is a method of developing and updating the system in a loop as time goes on. The pros focus on marketing and lowering failure of new releases. There are little to no drawbacks to DevOps in terms of post software development. This method is mostly focused on keeping an existing system updated and working rather than developing a new system. This means that it is not as great a methodology for our team at this time as we are not planning on consistently updating the software, as there is not any connection to the internet to the devices.

6.1.5 Software Development Method Choice

After carefully considering all of our different choices of software development, we have determined that for what we are dealing with the waterfall method makes the most sense. We are working with independent systems that will be easy to make work individually in stages. When a stage is done there will likely not be much way for it to break in the future when integrating different software with it. This method is also among the simplest of the different methodologies, making it easy to pick up for those of us who aren't super familiar with software development and its processes.

6.2 Embedded Software IDE

A software IDE (Integrated Development Environment) is a crucial piece of software development. It is a special piece of software that aids in developing other programs through the use of tools such as debuggers, auto generation of code, and many more. Some of these IDE's include, but are not limited to, Code Composer Studio, Visual Studio, Visual Studio Code, and tons and tons more with special features that have some quality-of-life upgrades to them.

Because of our selection of the ATmega1280, we need to make sure that we have an IDE that can compile our program down to the right instructions that this microprocessor can understand. One such IDE that does this is the Arduino IDE. This is an open-source software that allows for the programming of all sorts of Arduino support microprocessors. This is a very high-level programming language meaning that it has a lot of abstraction making it very easy to interface the processor. The Arduino IDE also allows access to a debugger on top of all of its other quality features that allows for rapid development.

6.3 Image Recognition

In order to do any sort of classification on images, there needs to be something that can actually detect what is in the images. Images just like any other data on computers, is just a series of bits that are 0's or 1's. In order to pull data out of these images we need a sophisticated kind of software known as artificial intelligence. In image classification this is generally known as a neural network. There are many different kinds of neural networks out there and different frameworks that interface these networks. In the upcoming section we will discuss how we chose our network framework as well as how we trained it to find data that we needed it to find.

6.3.1 Image Recognition Framework Choice

In image recognition there are many different frameworks to choose from. A few of these that we considered all have python libraries that make it really easy to access with our chose Jetson Nano. Some of the libraries we considered are OpenCV, Scikit-Image, SciPy, Pillow, NumPy. In the end many of these libraries do the same thing just using different syntax, so we ended up choosing the one that is very high in popularity, OpenCV. OpenCV is an open-source computer vision library that was developed by Intel in 2000. Due to its popularity, this library comes with many different examples of how to use it and very large amounts of documentation.

Along with the computer vision we also need a neural network to be able to pass the images through to correctly identify them. In picking our neural network framework to use we ended up going with TensorFlow. TensorFlow is another very widely used neural network framework developed by Google that has many different tutorials and examples to work through. These

examples were pivotal in making the network to classify birds and trash in reasonable amounts of time.

We plan on using a supervised learning approach to machine learning. Supervised learning is where the correct label is known during training. This is used to correctly identify whether the model has predicted accurately or not accurately during the training phase of the model. The labels must be given by the dataset or labeled by us during the cleaning phase of training where all the data must have the correct values. The weights get adjusted appropriately based on these labels that is given. This is different from semi-supervised and unsupervised training where the model has unlabeled data, and it learns to find patterns in the data to classify. Since we already have labeled data there isn't much reason to work through unsupervised learning of any sort in our case.

6.3.2 Training Platform

Any use of a neural network means that there needs to be training of the network. Training a neural network takes a lot of computational power, as well as a lot of data. Training a network on image detection using the Jetson Nano isn't exactly feasible if we want our project to be done on time. In order to train the network, we need to train the model using external resources and compile the model down to just have its weights on the final product. We used Google Collaboratory to train the TensorFlow model using cloud-based resources. This allowed us to edit code and retrain the network from anywhere that had internet access. This hastened the development of making the image classification models. In Google Collaboratory they give free access to a GPU that can train neural networks. After everything is done in Google Collaboratory, it is as simple as downloading the python script and the compiled model onto the Jetson Nano and running the script.

6.3.3 Training Data

In order to train a neural network to classify things properly, there needs to be data for the network to learn on. The data we used for image classification was first found from a dataset on Kaggle. Kaggle is one of the world's largest data science communities with many different datasets and tools to help machine learning applications. Kaggle is free and open source allowing us to grab data very easily from the database. The dataset we chose was an image classification for classifying 525 different bird species. This dataset came with just over 80000 images to train and validate the model with. The main goal of this image classifier is not to classify what kind of bird lands in front of our camera, instead it is to just identify if it is a bird or not. A binary classifier such as this will become very skewed if all we give it to train on are images of birds. It would just classify bird 100 percent of the time rather than actually learning anything. So, to add some variance into our data we used another Kaggle dataset that was meant for classification of animals. This was another dataset made with the intention of classifying different kinds of animals.

The trash dataset was a bit harder to find something would be helpful with what we are trying to see. Our main goal is to make the model be able to be a binary classifier that can classify cigarettes versus non-cigarettes. As a team we couldn't find any dataset that had what we were looking for, so we made our own dataset. This dataset consisted of images that we took of cigarettes in a trash chamber and filled it with images of sticks and other things birds may bring. This then gets further filled in the programming stage with data augmentation.

We wrote a small script that could clean our data so that instead of classifying the kinds of birds and kinds of animals we just had 2 folders. One of these folders was populated with birds, the other

folder being populated with non-birds. This was now the data being used to train with on the neural network image classification.

6.3.4 Training Neural Network

In training the network originally, we attempted to make our own model from scratch. This proved to be a very challenging endeavor with results consistently not able to match anything in pictures. While doing research on how to improve our training to be able to properly classify images, we discovered transfer learning. Transfer learning is a technique that reuses a pre-trained model on a new problem. We used a model from TensorFlow Hub that could classify over 800 different species of birds using the MobileNet V2 architecture. Since we want a model that can classify if we are looking at a bird or not this is perfect for retraining our system. In order to use this in our model we perform feature extraction and use our training data to squash down the 800 types of birds it can classify to be able to classify bird or not bird. This was very successful having a testing accuracy of over 95 percent before compiling down to TensorFlow Lite, which is just a more mobile friendly version of TensorFlow.

For the model that can recognize trash, this was a little bit harder to find a pretrained model on. So, the goal for this one is to use a generic model that is using one of the MobileNet neural network architectures. This will help in making the network as this is a generic computer vision model that is good at recognizing features in photos.

6.3.5 Compiling Model

After training our model, it gets compiled to run independently so that it doesn't have to be trained every single time it gets used. This is due to the large amounts of resources needed in training. This gets compiled down to TensorFlow Lite which is a lightweight version of TensorFlow making it take less resources in total to use. As any tradeoff less resources also mean less accuracy. After transferring to the Lite model, we still achieved a testing accuracy of 90 percent on the bird classification.

6.4 PCB Software

7. Prototype Fabrication

7.1 3D Printing

7.2 Circuit Design

8. Prototype Testing

9. Administrative Content

9.1 Organizational Software Used

In order to maintain a seamless flow of communication and ensure that all team members remained well-informed about any modifications, we strategically leveraged an array of diverse organizational tools. These instrumental tools served as the linchpin of our collective success, enabling us to harmoniously pursue our shared objectives while working autonomously.

9.1.1 Discord

Discord was the most important tool we used to keep communication with everyone on the team. Discord has many different features that really made it stand out as our main form of communication. Members of our group were already very familiar with discord and all of its amazing features that it has to offer. Discord started as a platform mostly for gamers to voice chat and over the years turned into the Discord we know today.

The main feature that made Discord so appealing to our team is the use of making servers with different channels. Servers are a way of having everyone in one group to be able to see all forms of information being posted. Inside of these servers we have different text channels that form independent information from each other. That means that different topics can be isolated to that channel. For example, there could be a channel that is for a section on only printed circuit boards or a channel that is meant for software development. This helps keep information neatly organized and easy to find whenever necessary. This allowed for us to develop our project without the stress of looking through mass messages that other group communication might run into. Inside of these channels there is even more organization tools allowing for pinning of posts. When a post gets pinned, it can then be accessed from an external button rather than having to even scroll through a channel. This is a great way to have important information and deadlines posted that can always be checked right away. Just as every channel is independent of each other, so are the pins from the channels.

As an added bonus these text channels can be used to post media of any kind. We had a dedicated channel to tutorials any time we found a useful link that had a video describing something similar to what we were needing to do. Along with links to different YouTube tutorials or links to products found on the internet, we could also post pictures and videos. This feature became very useful in testing our bird classifier. Since we can't always be together, we could test images taken from the camera we are planning to use for our project and pass that into the model to classify the bird. In addition to media being posted discord also allows for code to be posted. This means that whenever one of us is working on code from another device that is not cloud based, we would be able to send it to each other very easily and quickly. This helped for rapid debugging and development of software.

9.1.2 Draw.io

Our team used Draw.io to create our hardware schematics to divide the work amongst the students. Draw.io is a free, open-source diagramming tool primarily used for creating various types of diagrams and visual representations. It is a web-based application that allowed us to create the visuals necessary to explain how our project will run. The overall optical systems and electromechanical components were placed in ways to explain how certain functions of the BIRDS will begin and what other functions they will trigger.

9.1.3 ChatGPT

In the research and writing stage of our project, we utilized ChatGPT by OpenAI to get a better idea of how to structure our topics. Simple and complex research questions were asked of the large language model (LLM)

9.1.4 GitHub

While working on the website for all of our information for senior design, we found that we were having a lot of times where we would change code or accidentally break something when trying out a new feature. That is when we remembered the very popular version control platform GitHub. GitHub is a version control platform that allows for users to store entire folder directories on a cloud-based storage. From there anyone with access to the GitHub repository can push, pull, and clone the folder onto their local machine. This allowed for development between different users as well as different machines. On top of being able to develop from different places it has the ability to rollback code to previous states, hence the name version control. It does this by taking advantage of having branches in code. A branch is almost like a new section of code that is generally made to create a new feature of some kind or edit a previously existing feature. If for whatever reason something breaks in already working code, then the branch can be dropped and rolled back to a previous working version. If the new feature does work, then that new bit of code can be merged into the main branch making it the newest version of working code. This helps in developing and will continue to help on our journey as we create software for both machine learning and for microcontroller programming.

9.2 Budget

Table 9.2. Budget

| Item | Price | Quantity |
|---------------------|-------------|----------|
| Microcontroller | \$10 | 1 |
| Nvidia Jetson Nano | \$150 | 1 |
| IR Sensor | \$50 | 1 |
| Motor | \$10 | 5 |
| Battery | \$23 | 1 |
| Solar | \$50 | 1 |
| LED Light Source | \$15 | 10 |
| Objective Lens | \$50 | 2 |
| Collimating Lens | \$30 | 2 |
| Focusing Lens | \$50-\$100 | 2 |
| Diffraction Grating | \$20-\$30 | 2 |
| CMOS | \$150-\$200 | 2 |
| Custom PCB | \$20-\$30 | 1 |

| | | |
|------------------|-------------|---|
| Housing Material | \$20 | 1 |
| Total | \$558-\$768 | |

9.3 Milestones

Table 9.3. Milestones for Senior Design 1

| Milestone | Start Date | End Date | Milestone Description |
|--------------------------|------------|----------|--|
| Form Group | 8/22/23 | 8/22/23 | Begin the process of forming a group and begin to set up proper communication methods. |
| Brainstorm Ideas | 8/22/23 | 8/28/23 | Brainstorm ideas that will meet the scope of engineering projects for senior design. |
| Project Selection | 8/28/23 | 9/1/23 | Selecting one of the projects from the list of prospective projects from brainstorming. |
| Divide & Conquer | 9/1/23 | 9/15/23 | The official presentation of our project idea and a small list of requirements, parts, and general ideas of our plans. |
| Website | 9/1/23 | 12/5/23 | Setup up the website that will have all of our supporting documentation, as well as some extra introductions and descriptions. |
| Divide & Conquer Meeting | 9/20/23 | 9/20/23 | Meeting with committee and senior design professors to discuss our proposal. |

| | | | |
|---------------------------|---------|----------|---|
| Divide & Conquer Revision | 9/20/23 | 9/25/23 | Make revisions to our proposal and any other details that will be transferred to the bigger paper later. |
| 60 Page Draft | 9/20/23 | 11/3/23 | The draft of what will come to the final paper. This will include some of the needed topics from the final paper requirements. |
| 100 Page Report | 9/20/23 | 11/23/23 | This will be the final meeting to go over any formatting issues before the final submission of the report. |
| Final Paper | 9/20/23 | 12/5/23 | This will be the final project report and will have all of the design specs, philosophies, and research that we did as a group. |
| Prototype | 11/1/23 | 12/5/23 | This will be a working prototype of our design that will showcase what our design can do. |

Table 9.3. Milestones for Senior Design 2

| Milestone | Start Date | End Date | Milestone Description |
|--------------------|------------|----------|--|
| Order Parts | 1/8/24 | 1/15/24 | This will be the time to finalize all the parts we need and make sure everything is ordered and on the way. |
| Build Subsystems | 1/15/24 | 2/15/24 | This will be time to get all the subsystems working independently of each other |
| Integration | 2/15/24 | 3/15/24 | Bring all the subsystems together to work out what does and doesn't work together |
| Testing | 3/15/24 | 4/15/24 | After getting all the subsystems together this time will be meant for testing everything together and seeing how it works in practice. |
| Presentation Prep | 4/15/24 | 4/24/24 | Getting all the necessary materials ready for the presentation of our materials |
| Final Presentation | 4/24/24 | 4/30/24 | This will be the final presentation for Senior Design 2 marking a finished working product |

10. Conclusion

Concluding statements...

Appendix A – References

Bibliography

Klein, J. (2008, March). A thought experiment on the intelligence of crows. TED.

3.0: Existing Similar Products

- Crow box
- Smart Bird Feeder

3.1:

1. Ted Talk - Joshua Klein
2. <https://www.pnas.org/doi/10.1073/pnas.1517131113>

3.1.1

3. <https://www.insidescience.org/news/new-caledonian-crows-keep-their-favorite-tools-safe#:~:text=New%20Caledonian%20crows%20are%20one,the%20island%20called%20Desmanthus%20virgatus.>
4. <https://royalsocietypublishing.org/doi/10.1098/rsos.160439>
5. <https://www.pnas.org/doi/abs/10.1073/pnas.80.14.4394>
6. <https://link.springer.com/article/10.1007/s10071-006-0064-1>
7. <https://www.pbs.org/lifeofbirds/brain/#:~:text=Carrion%20crows%20and%20humans%20line,the%20nuts%20cracking%20them%20open.>
8. <https://edis.ifas.ufl.edu/publication/UW192>

Rodrigo:

[ATmega640/1280/1281/2560/2561 datasheet \(microchip.com\)](#)

3.2.5.3: Laser sensor

12. <https://opg.optica.org/optica/fulltext.cfm?uri=optica-2-7-607&id=321242>
13. https://www.researchgate.net/publication/323566527_High-Speed_High-Efficiency_Broadband_Silicon_Photodiodes_for_Short-Reach_Optical_Interconnects_in_Data_Centers

14. https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=285
15. <https://lednique.com/opto-isolators-2/light-dependent-resistor-ldr/>

3.3.1.4 Nvidia Jetson Nano

1. https://developer.download.nvidia.com/assets/embedded/secure/jetson/Nano/docs/JetsonNano_DataSheet_DS09366001v1.1.pdf?DI7q8vdCLgZ8hfzCCIw54SGMUDVfUjreojY7SF3qF2S0g9c3IXM394hDgH-rSKRUq4r7MpolJZmYQZ2mooWkyEbE6lqNOtlW68yTXsm68X-bpXnvIA3xiXnrgsvO0uz-rTkkUzJXJISEYP7jRyaCV6xG_QHcsaeroJ0dPbEzXQ7MdyxycyxKVoKeCDhBw==&t=eyJscyI6ImdzZW8iLCJsc2QiOiJodHRwczovL3d3dy5nb29nbGUuY29tLyJ9

3.3.1.1 Raspberry Pi 4

1. <https://datasheets.raspberrypi.com/rpi4/raspberry-pi-4-datasheet.pdf>

3.3.1.2 Coral USB Accelerator

1. <https://coral.ai/docs/accelerator/datasheet/>

3.3.1.3 Coral Dev Board

1. <https://coral.ai/docs/dev-board/datasheet/#features>

3.3.2.4: Benchmarks

1. <https://aallan.medium.com/benchmarking-tensorflow-lite-on-the-new-raspberry-pi-4-model-b-3fd859d05b98>

3.4: Optical systems

16. <https://www.flir.com/support-center/iis/machine-vision/knowledge-base/key-differences-between-ccd-and-cmos-imaging-sensors/>

3.4.1: CMOS

17. (wills figure) http://www.optique-ingenieur.org/en/courses/OPI_ang_M05_C06/co/Contenu_20.html
18. <https://www.svs-vistek.com/en/knowledgebase/svs-about-machine-vision.php?p=cmos-sensor-technology-456#:~:text=CMOS%20%2D%20Flexible%20and%20fast%20sensor,as%20%E2%80%9CActive%20Pixel%20Sensors%E2%80%9D>

3.4.2: CCD

16. <https://www.flir.com/support-center/iis/machine-vision/knowledge-base/key-differences-between-ccd-and-cmos-imaging-sensors/>

3.4.4

19. figure <https://www.e-consystems.com/blog/camera/technology/mipi-camera-vs-usb-camera-a-detailed-comparison/>

18. <https://www.svs-vistek.com/en/knowledgebase/svs-about-machine-vision.php?p=usb3-interface-456>

3.4.5 Bird Lens System

1. (Figure 3.4.5.1) <https://www.edmundoptics.com/knowledge-center/application-notes/imaging/understanding-focal-length-and-field-of-view/#:~:text=The%20first%20and%20often%20easiest%20option%20is%20to,lens%20with%20one%20of%20a%20different%20focal%20length> (Figure 2 on webpage)

3. (Figure 3.4.5.3) <https://www.edmundoptics.com/knowledge-center/application-notes/imaging/depth-of-field-and-depth-of-focus/> (Figure 3 on webpage)

(Contact for getting permission: sales@edmundoptics.com)

3.4.6 Trash lens system

20. <https://www.specim.com/hyperspectral-imaging-applications/hyperspectral-imaging-in-recycling-and-waste-management/>

21. [https://www.globalspec.com/learnmore/optical_components_optics/optical_components/optical_lenses#:~:text=Lenses%20come%20in%20a%20variety,positive%20meniscus%20and%20negative%20meniscus.&text=Lenses%20can%20be%20classified%20into,negative%20\(or%20diverging\)%20lenses](https://www.globalspec.com/learnmore/optical_components_optics/optical_components/optical_lenses#:~:text=Lenses%20come%20in%20a%20variety,positive%20meniscus%20and%20negative%20meniscus.&text=Lenses%20can%20be%20classified%20into,negative%20(or%20diverging)%20lenses).

21. figure [https://www.globalspec.com/learnmore/optical_components_optics/optical_components/optical_lenses#:~:text=Lenses%20come%20in%20a%20variety,positive%20meniscus%20and%20negative%20meniscus.&text=Lenses%20can%20be%20classified%20into,negative%20\(or%20diverging\)%20lenses](https://www.globalspec.com/learnmore/optical_components_optics/optical_components/optical_lenses#:~:text=Lenses%20come%20in%20a%20variety,positive%20meniscus%20and%20negative%20meniscus.&text=Lenses%20can%20be%20classified%20into,negative%20(or%20diverging)%20lenses).

22. <https://www.newport.com/g/spherical-lens-selection-guide>

3.5.1 Arduino Mega 2560

1. <https://store-usa.arduino.cc/products/arduino-mega-2560-rev3?selectedStore=us>

5.2.1: Trash Imaging System

31. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5730088/#:~:text=Cigarette%20lengths%20generally%20fall%20into,ranging%20from%20110%20to%20121mm>.

6.1: Software Development

1. <https://www.synopsys.com/blogs/software-security/top-4-software-development-methodologies.html>
2. <https://www.geeksforgeeks.org/software-engineering-spiral-model/#>

6.2: Image Recognition

1. <https://neptune.ai/blog/image-processing-python-libraries-for-machine-learning>

6.2.2: Training Platform

1. <https://colab.research.google.com/>

6.3.3: Training Data

1. <https://www.kaggle.com/datasets/gpiosenska/100-bird-species>
2. <https://www.kaggle.com/datasets/alessiocorrado99/animals10>

6.3.4: Training Neural Network

1. https://tfhub.dev/google/lite-model/aiy/vision/classifier/birds_V1/3

Appendix B – Copyright Permissions

Refers to Figure 3.4.4 Interfacing Comparison Chart



Eric S <eric.s@e-consystems.com>

To: Aiden Nipper

Cc: +3 others

Hi Aiden,

Good day!

Thanks for writing your requirement with us.

Yes you can use the image for your Journal!

It would be great if you could share the Link for the Journal after it has been published.

Happy to help and assist if anything needed further.

Stay safe and healthy!

Thanks and Regards,

Eric S

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Appendix C – ChatGPT

[GPT – COMPONENT RESEARCH]

A continuous conversation with ChatGPT 3.5:

Prompt 1:

“i am writing a IEEE project report and i need to add a section on researching possible technologies to use for actuators. how does a DC motor work”

Answer 1:

“A DC (direct current) motor is a common type of electric motor that converts electrical energy into mechanical motion. It operates based on the principles of electromagnetic induction and the Lorentz force, which are fundamental concepts in electromagnetism. Here's a simplified explanation of how a DC motor works:

1. **Basic Components:**

- **Armature:** The central rotating component of the motor, typically a coil of wire.
- **Stator:** The stationary part of the motor, which houses magnets or field windings.
- **Commutator:** A split ring attached to the armature that reverses the direction of the current flow through the coil.

2. **Magnetic Field:**

Inside the motor, there are two magnetic fields:

- **Stator Magnetic Field:** This is typically generated by permanent magnets or field windings (coils of wire carrying a constant current). It creates a fixed magnetic field within the motor.
- **Armature Magnetic Field:** The armature (coil of wire) also produces a magnetic field when an electric current flows through it.

3. **Lorentz Force:**

When a current flows through the coil in the armature, it generates a magnetic field. This magnetic field interacts with the fixed stator magnetic field, resulting in the Lorentz force. The Lorentz force causes the coil to experience a torque (rotational force).

4. **Rotation:**

As the coil experiences the torque, it starts to rotate. The commutator, a split ring, is crucial in this process. It periodically reverses the direction of the current flowing through the coil as it rotates. This reversal of current changes the direction of the magnetic field in the coil, which keeps the motor spinning in the same direction.

5. **Continuous Rotation:**

By maintaining the constant flow of current and reversing it at the right moments with the help of the commutator, the DC motor can achieve continuous rotation. The speed and direction of rotation can be controlled by adjusting the voltage and polarity of the applied current.

It's important to note that there are various types of DC motors, including brushed and brushless DC motors, which differ in terms of the commutation method and efficiency. The principles

described above apply primarily to brushed DC motors. Brushless DC motors use electronic controllers and sensors to achieve commutation without physical brushes and commutators, offering improved efficiency and reliability.

When researching possible technologies for actuators in your IEEE project report, you can consider both brushed and brushless DC motors, as well as other types of actuators such as stepper motors, servo motors, pneumatic actuators, and more, depending on your specific application requirements. Each type of actuator has its advantages and disadvantages, and the choice will depend on factors like precision, speed, torque, and control requirements for your project.”

Prompt 2:

“could you rephrase it in a few paragraphs”

Answer 2:

“Certainly, here's a more concise explanation of how a DC motor works:

A DC (direct current) motor is an electric motor that converts electrical energy into mechanical motion. It operates on the principles of electromagnetic induction and the Lorentz force. The motor consists of an armature (a coil of wire), a stationary stator (containing magnets or field windings), and a commutator (a split ring attached to the armature).

When an electric current flows through the coil in the armature, it generates a magnetic field. This magnetic field interacts with the fixed stator magnetic field, resulting in the Lorentz force, which creates a torque, causing the armature to rotate. The commutator is responsible for reversing the direction of the current flow in the coil, ensuring continuous rotation of the motor.

There are various types of DC motors, including brushed and brushless varieties, which differ in commutation methods and efficiency. Brushed DC motors use physical brushes and a commutator, while brushless DC motors employ electronic control and sensors for commutation, offering improved efficiency and reliability. When researching technologies for actuators in your project, consider the specific requirements of your application, as various types of actuators, including different motor types and non-electric actuators like pneumatics, may be suitable based on your needs.”

Prompt 3:

“explain how does a stepper motor works”

Answer 3:

“A stepper motor is an electromechanical device that converts electrical pulses into precise and incremental rotational motion. Unlike traditional DC motors or servo motors, which rotate continuously, stepper motors move in discrete steps, making them well-suited for applications that require accuracy and control. Here's how a stepper motor works:

1. **Basic Components:**

- **Stator:** The stationary part of the motor, typically made up of multiple coils or windings.
- **Rotor:** The rotating part of the motor, usually consisting of a toothed gear or shaft.
- **Magnetic Poles:** The stator poles are magnetized to create a magnetic field.

2. **Phases and Windings:**

A stepper motor can have multiple phases, typically two or four. Each phase consists of a coil or winding, and they are electrically energized in a specific sequence to produce rotation.

3. **Magnetic Attraction:**

The rotor of the stepper motor has teeth or magnetic regions, which align with the magnetic poles of the stator. When a particular phase is energized, the magnetic field produced by that phase attracts the rotor's teeth or magnetic regions.

4. **Step Sequence:**

Stepper motors operate in discrete steps. To make the motor move, you energize the coils in a specific sequence. The most common sequences are "full step" and "half step." In a full step, each phase is energized one at a time, and in a half step, two phases can be energized simultaneously at varying levels to achieve smaller steps.

5. **Direction Control:**

By changing the order in which the phases are energized and the duration of each phase, you can control the direction and speed of rotation. Reversing the sequence or changing the timing reverses the motor's rotation.

6. **Precise Control:**

Stepper motors provide precise control over the rotation angle and can move in very small increments, making them suitable for applications such as 3D printers, CNC machines, and robotics.

7. **Open-Loop Operation:**

Stepper motors are typically used in an open-loop system, meaning there is no feedback mechanism to verify the motor's position. However, this can lead to issues like missed steps if the load becomes too great or if the motor is overdriven.

8. **Driver Electronics:**

To control a stepper motor, you need a stepper motor driver or controller, which generates the necessary sequence of electrical pulses to energize the motor's coils in the correct order and timing.

Stepper motors are popular for applications where precision and position control are essential, as they offer a straightforward and predictable way to achieve discrete and controlled rotational motion. Their simplicity and reliability make them well-suited for a wide range of industrial and hobbyist applications.”

Prompt 4:

“rephrase it in a few paragraphs”

Answer 4:

“A stepper motor is an electromechanical device that translates electrical pulses into precise and incremental rotational movement. Unlike conventional motors that rotate continuously, stepper motors operate in distinct steps, making them ideal for applications requiring fine control and accuracy. Here's a breakdown of how a stepper motor functions:

A stepper motor consists of two key components: the stator and the rotor. The stator comprises coils or windings, while the rotor is equipped with teeth or magnetic areas that interact with the stator's magnetic poles.

Stepper motors are categorized by the number of phases they possess, typically two or four. Each phase involves a coil that can be electrically energized in a particular sequence to induce rotation.

To initiate movement, a specific phase is energized, and the magnetic field generated by that phase draws the rotor's teeth or magnetic regions towards it. These motors operate in discrete steps, with common sequences being "full step" and "half step." In full-step mode, each phase is energized sequentially, while in half-step mode, two phases can be energized simultaneously at varying levels to achieve smaller steps.

Stepper motors provide meticulous control over the angle of rotation, enabling precise positioning. By adjusting the order and duration of phase energization, you can manage the motor's direction and speed. Reversing the sequence or altering the timing reverses the motor's rotation.

Stepper motors do not require feedback mechanisms for position verification, operating in an open-loop system. However, this simplicity can lead to issues such as missed steps if the motor faces excessive loads or overdriving. To control a stepper motor effectively, a dedicated stepper motor driver or controller is necessary. This device generates the required sequence of electrical pulses to energize the motor's coils correctly in terms of order and timing.

Stepper motors find extensive use in applications where precision and precise position control are crucial, offering a reliable and predictable means of achieving controlled rotational motion in discreet increments. Their straightforward operation and reliability make them highly suitable for a broad array of industrial and hobbyist applications.”

Prompt 5:

“explain how servo motors work”

Answer 5:

“A servo motor is a rotary actuator that allows for precise control of angular position, speed, and acceleration. It is widely used in applications that require accurate and controlled motion, such as robotics, industrial automation, and aerospace systems. Here's how a servo motor works:

1. **Basic Components:**

- ****Motor****: The core of the servo motor is a regular DC motor or a brushless DC motor.
- ****Position Feedback Device****: This is typically a potentiometer or an encoder that provides feedback on the motor's current position.
- ****Control Circuitry****: A control system, often called a servo drive or amplifier, interprets the desired position and compares it to the actual position feedback.
- ****Gears****: Some servo motors have gears to increase torque and reduce the speed of the output shaft.

2. **Feedback System:**

The key to a servo motor's precision is its closed-loop control system. The position feedback device continuously monitors the motor's shaft position and reports it to the control circuitry. This feedback mechanism ensures that the motor knows its current position at all times.

3. **Setpoint and Error Calculation:**

You specify a target or setpoint position for the servo motor. The control circuit calculates the error, which is the difference between the desired position and the current position.

4. ****Control Signal:****

The control circuit computes the control signal based on the error and sends it to the motor. This control signal typically takes the form of a pulse-width-modulated (PWM) signal. The control signal adjusts the voltage or current supplied to the motor.

5. ****Motor Movement:****

The motor responds to the control signal and starts moving. It will continue to move until the feedback system reports that the desired position has been reached.

6. ****Continuous Adjustment:****

The servo motor continuously adjusts its position by comparing the feedback with the desired position. It responds rapidly to any deviations, making it suitable for applications that require precise and real-time control.

7. ****Speed and Acceleration Control:****

Servo motors not only control position but also speed and acceleration. By modulating the control signal, you can achieve smooth and controlled motion profiles.

8. ****Torque Output:****

Servo motors provide a high level of torque even at low speeds, making them ideal for applications that require both accuracy and strength.

9. ****Applications:****

Servo motors are commonly used in robotics, CNC machinery, conveyor systems, camera gimbals, and many other applications where precise and adjustable motion control is necessary.

In summary, a servo motor is an electromechanical device that uses a closed-loop control system to maintain and adjust its position. The position feedback mechanism continuously monitors the motor's actual position and ensures it closely matches the desired position, allowing for precise and dynamic control of motion.”

Prompt 6:

“rephrase it in a few paragraphs”

Answer 6:

“A servo motor is a precision-based rotary actuator known for its ability to provide accurate control over angular position, speed, and acceleration. It is a fundamental component in applications demanding meticulous and controlled motion, like robotics, industrial automation, and aerospace systems. The operation of a servo motor can be explained as follows:

At its core, a servo motor consists of several essential elements, including the motor itself, a position feedback device (commonly a potentiometer or encoder), control circuitry (referred to as a servo drive or amplifier), and in some cases, gears to modify torque and speed on the output shaft.

The servo motor's precision arises from its closed-loop control system. This system employs the position feedback device to continually monitor the motor's current shaft position. This real-time feedback ensures that the motor is always aware of its exact position.

To guide the servo motor's movement, a target position, also known as the setpoint, is specified. The control circuit calculates the error, which represents the variance between the desired position and the motor's actual position.

A control signal, often in the form of a pulse-width-modulated (PWM) signal, is computed by the control circuit based on the error calculation. This signal regulates the voltage or current supplied to the motor, influencing its movement.

The motor responds to the control signal and initiates motion, adjusting itself until the feedback system confirms alignment with the desired position.

The servo motor continually fine-tunes its position by assessing the feedback against the target position, enabling it to respond quickly to any deviations. This adaptability makes servo motors well-suited for applications demanding precise and real-time control.

In addition to position control, servo motors also manage speed and acceleration. By modulating the control signal, they deliver smooth and controlled motion profiles. Furthermore, servo motors offer substantial torque output, even at low speeds, catering to applications that require both accuracy and strength.

Servo motors find wide application in diverse fields, including robotics, CNC (computer numerical control) machinery, conveyor systems, camera gimbals, and various scenarios where precise, adjustable, and dynamic motion control is essential.”

Prompt 7:

“how do lithium-ion batteries work”

Answer 7:

“Lithium-ion (Li-ion) batteries are rechargeable energy storage devices commonly found in numerous portable electronics, electric vehicles, and more. They function based on the movement of lithium ions between two electrodes within the battery. Here's a simplified explanation of how lithium-ion batteries work:

1. **Basic Components:**

A typical lithium-ion battery consists of three main components:

- ****Positive Electrode (Cathode):**** Made of a lithium-based compound, usually lithium cobalt oxide (LiCoO₂), lithium iron phosphate (LiFePO₄), or other materials.
- ****Negative Electrode (Anode):**** Typically made of carbon (graphite) that can intercalate (absorb) lithium ions.
- ****Electrolyte:**** A lithium salt dissolved in a solvent, which allows for the movement of lithium ions between the cathode and anode.

2. **Charging Process (Li-ion Intake):**

When you charge a Li-ion battery, an external voltage source (like a charger) applies a voltage across the battery terminals. This voltage causes lithium ions to move from the positive cathode to the negative anode through the electrolyte. The lithium ions are stored in the anode's carbon structure.

3. **Discharging Process (Li-ion Release):**

When you use the battery to power a device, the stored lithium ions in the anode begin to move back towards the cathode through the electrolyte. This movement of lithium ions creates an electric current, which powers the device.

4. ****Ion Movement:****

During both charging and discharging, lithium ions move back and forth between the anode and cathode. This ion movement is accompanied by the flow of electrons in the external circuit, producing electric energy.

5. ****Chemical Reactions:****

The movement of lithium ions is facilitated by chemical reactions that occur at the electrode surfaces. These reactions involve the exchange of electrons between the cathode and anode materials. These chemical processes are reversible, allowing the battery to be charged and discharged repeatedly.

6. ****Safety Mechanisms:****

Lithium-ion batteries are equipped with safety features to prevent overcharging and overheating, which can lead to safety hazards. These features include protection circuits and thermal management systems.

7. ****Voltage and Capacity:****

The voltage and capacity of a Li-ion battery are determined by the specific materials used in the cathode and anode. Different materials yield various voltage ranges (typically around 3.6 to 3.7 volts for most Li-ion batteries) and energy storage capacities.

8. ****Cycle Life:****

Li-ion batteries have a limited number of charge and discharge cycles before their capacity degrades. The cycle life varies depending on the battery's design and usage conditions.

Lithium-ion batteries have become ubiquitous due to their high energy density, rechargeability, and relatively low self-discharge rate. However, they do require proper care to prolong their lifespan and ensure safe operation, such as avoiding extreme temperatures and not overcharging or discharging them excessively. Advances in Li-ion battery technology continue to improve their performance, energy density, and safety, making them a key component in modern electronics and electric vehicles.”

Prompt 8:

“rephrase it in a few paragraphs”

Answer 8:

“Lithium-ion (Li-ion) batteries are rechargeable power sources found in a wide range of portable devices, including smartphones, laptops, and electric vehicles. The fundamental operation of these batteries relies on the movement of lithium ions between two critical components within the battery structure. Here's a simplified breakdown of how lithium-ion batteries work:

A typical Li-ion battery comprises three key elements: a positive electrode (cathode) made of a lithium-based compound, a negative electrode (anode) usually composed of carbon (graphite), and an electrolyte solution containing a lithium salt in a solvent. The interplay of these components is central to the battery's functioning.

During the charging process, an external voltage source, like a charger, applies a voltage across the battery's terminals. This voltage drives lithium ions from the cathode to the anode, where they become embedded within the carbon structure of the anode, effectively storing electrical energy.

In contrast, during discharge, when the battery powers a device, the stored lithium ions begin their journey back to the cathode through the electrolyte. This movement of lithium ions generates an electric current, which is harnessed to operate the device. The movement of ions is closely associated with the flow of electrons in the external circuit, resulting in the production of electrical energy.

The transfer of lithium ions between the cathode and anode is facilitated by chemical reactions at the electrode surfaces. These reactions involve the exchange of electrons, and they are entirely reversible, enabling the battery to be charged and discharged repeatedly. Lithium-ion batteries also incorporate safety mechanisms, including protection circuits and thermal management systems, to safeguard against overcharging and overheating, mitigating potential safety risks. The specific voltage and capacity of a Li-ion battery are determined by the particular materials employed in the cathode and anode. Variations in these materials lead to different voltage ranges and energy storage capacities. However, it's essential to note that Li-ion batteries have a finite number of charge and discharge cycles before their capacity diminishes, which varies depending on factors like battery design and usage conditions.

In conclusion, the widespread adoption of lithium-ion batteries is attributed to their high energy density, reusability, and relatively slow self-discharge rate. Nonetheless, ensuring their longevity and safe operation necessitates responsible handling, including avoiding extreme temperature conditions and refraining from excessive overcharging or discharging. Ongoing advancements in Li-ion battery technology continue to enhance their performance, energy storage capacity, and safety features, making them a vital component in the modern world of electronics and electric vehicles.”

Prompt 9:

“how do lithium-ion batteries work”

Answer 9:

“Lithium-polymer (LiPo) batteries are a type of rechargeable battery commonly used in various electronic devices, including remote-controlled vehicles, drones, and radio-controlled gadgets. They work on principles similar to lithium-ion batteries but use a different electrolyte and packaging. Here's how lithium-polymer batteries work:

1. **Composition:**

LiPo batteries consist of multiple layers of a flexible, porous polymer separator impregnated with an electrolyte, along with positive and negative electrodes. The positive electrode typically contains lithium cobalt oxide (LiCoO₂), while the negative electrode often includes graphite.

2. **Electrolyte:**

Unlike the liquid electrolyte found in traditional lithium-ion batteries, LiPo batteries use a solid or gel-like electrolyte. This polymer-based electrolyte is less prone to leakage and allows for flexible packaging.

3. **Ionic Movement:**

During the charging and discharging process, lithium ions move between the positive and negative electrodes through the solid or gel-like electrolyte. This ionic movement is what stores and releases electrical energy.

4. ****Charging (Lithium-ion Intake):****

When you charge a LiPo battery, an external power source applies a voltage across the battery terminals. This voltage drives lithium ions from the positive electrode (cathode) to the negative electrode (anode) through the polymer electrolyte. The energy is stored in the form of chemical potential.

5. ****Discharging (Lithium-ion Release):****

When the battery is used to power a device, the lithium ions migrate back from the anode to the cathode through the solid or gel-like electrolyte. As they return, they release the stored energy, generating an electric current that powers the device.

6. ****Safety Considerations:****

LiPo batteries are known for their light and flat pouch-like design, which makes them suitable for various applications. However, they can be sensitive to overcharging, over-discharging, and physical damage. Overcharging or puncturing the pouch can lead to thermal runaway and, in extreme cases, fires or explosions. Therefore, proper handling and care are crucial.

7. ****Voltage and Capacity:****

LiPo batteries come in various voltages and capacities, depending on their size and the specific application they are designed for.

8. ****Advantages:****

LiPo batteries offer several advantages, including high energy density, lightweight and flat form factor, and the ability to be molded into various shapes. These characteristics make them particularly suitable for applications requiring compact and custom-fit energy sources.

In summary, lithium-polymer batteries function similarly to lithium-ion batteries in terms of the movement of lithium ions between the positive and negative electrodes during charging and discharging. However, they use a solid or gel-like polymer electrolyte, which allows for more flexible packaging and provides advantages such as light weight and the ability to fit various form factors. Proper handling and charging are essential to ensure their safety and longevity.”

Prompt 10:

“rephrase it in a few paragraphs”

Answer 10:

“Lithium-polymer (LiPo) batteries, like their lithium-ion counterparts, are rechargeable power sources found in numerous electronic devices, particularly in applications where a flat and lightweight design is essential. The operational principles of LiPo batteries share commonalities with lithium-ion batteries, yet they exhibit distinctive characteristics. Here's an overview of how LiPo batteries function:

LiPo batteries are constructed with multiple layers of a flexible, porous polymer separator embedded with an electrolyte. These layers encompass positive and negative electrodes, with the

positive electrode often containing lithium cobalt oxide (LiCoO₂) and the negative electrode frequently including graphite.

What sets LiPo batteries apart is their utilization of a solid or gel-like electrolyte as opposed to the liquid electrolyte found in conventional lithium-ion batteries. This polymer-based electrolyte not only enhances safety by reducing the risk of leakage but also allows for a pliable packaging approach.

The operation of LiPo batteries revolves around the movement of lithium ions within the solid or gel-like electrolyte. During charging, an external power source applies voltage across the battery's terminals. This voltage initiates the migration of lithium ions from the positive electrode (cathode) to the negative electrode (anode) via the polymer electrolyte. The energy is stored in the form of chemical potential.

Subsequently, when the battery is employed to power a device, the lithium ions undertake a return journey from the anode to the cathode via the solid or gel-like electrolyte. In this process, the stored energy is liberated, generating an electric current that powers the device.

It is essential to exercise care when handling LiPo batteries due to their sensitivity to factors like overcharging, over-discharging, and physical damage. Mishandling can result in thermal runaway and, in severe instances, pose risks of fire or explosion. Thus, proper precautions and charging practices are imperative. LiPo batteries come in various configurations, varying in voltage and capacity, to suit different applications. Their attributes, such as high energy density and adaptable, flat form factor, make them an ideal choice for compact and customized energy solutions in a variety of scenarios.”

Prompt 11:

“how do NiMH batteries work”

Answer 11:

“Nickel-Metal Hydride (NiMH) batteries are rechargeable energy storage devices commonly used in various consumer electronics, such as cordless phones, digital cameras, and power tools. They function based on the movement of charged ions within the battery. Here's how NiMH batteries work:

1. **Basic Components:**

A typical NiMH battery consists of three primary components:

- ****Positive Electrode (Cathode):**** Made of a nickel oxyhydroxide compound (NiOOH).
- ****Negative Electrode (Anode):**** Composed of a hydrogen-absorbing alloy, often a mixture of metals like rare earth metals and nickel.
- ****Electrolyte:**** A potassium hydroxide (KOH) solution that enables the flow of ions between the anode and cathode.

2. **Charging Process (Nickel Oxide Formation):**

When you charge a NiMH battery, an external voltage source, such as a charger, applies a voltage across the battery terminals. This voltage causes nickel ions (Ni²⁺) to oxidize from the cathode, forming nickel oxide (NiOOH). Simultaneously, hydrogen ions (H⁺) are released at the anode.

3. **Discharging Process (Hydrogen Absorption):**

When the battery is used to power a device, the reverse process occurs. Hydrogen ions (H^+) at the anode react with the metal hydride alloy to release electrons, creating an electric current. Nickel oxide at the cathode accepts electrons and releases nickel ions (Ni^{2+}).

4. ****Ion Movement:****

During both charging and discharging, charged ions (nickel ions and hydrogen ions) move back and forth between the anode and cathode through the electrolyte. This ion movement is what stores and releases electrical energy.

5. ****Chemical Reactions:****

The chemical reactions that take place at the anode and cathode are reversible, allowing the battery to be charged and discharged multiple times. The transition between nickel oxide and metal hydride alloys is at the core of these reversible reactions.

6. ****Voltage and Capacity:****

NiMH batteries typically provide 1.2 volts per cell, which is lower than the 1.5 volts of alkaline batteries. However, they have higher capacity and are rechargeable, making them suitable for devices that require longer-lasting power.

7. ****Self-Discharge:****

One drawback of NiMH batteries is their relatively higher self-discharge rate compared to some other rechargeable batteries, which means they can lose stored energy over time, even when not in use.

NiMH batteries are known for their rechargeability, making them a cost-effective and environmentally friendly choice for many applications. However, they require proper care, including occasional full discharge and recharge cycles to maintain their performance and longevity. Advances in NiMH battery technology continue to improve their capacity and reduce self-discharge rates.”

Prompt 12:

“rephrase it into a few paragraphs”

Answer 12:

“Nickel-Metal Hydride (NiMH) batteries are rechargeable power sources widely utilized in various consumer electronics like cordless phones, digital cameras, and handheld tools. These batteries operate by enabling the movement of electrically charged ions within their structure. Here's a simplified account of how NiMH batteries work:

A standard NiMH battery consists of three primary constituents: a positive electrode known as the cathode, which is made from a compound containing nickel oxyhydroxide ($NiOOH$); a negative electrode, referred to as the anode, composed of a hydrogen-absorbing alloy, often featuring a blend of metals including rare earth metals and nickel; and an electrolyte, typically a potassium hydroxide (KOH) solution that facilitates the flow of ions between the anode and cathode.

During the charging process, when you connect a NiMH battery to an external voltage source, like a charger, a voltage is applied across the battery terminals. This voltage prompts the oxidation of nickel ions (Ni^{2+}) from the cathode, resulting in the formation of nickel oxide ($NiOOH$). Concurrently, hydrogen ions (H^+) are liberated at the anode.

When the battery is deployed to power a device, the inverse of the charging process unfolds. Hydrogen ions (H^+) at the anode engage with the metal hydride alloy, leading to the release of electrons, thus generating an electric current. Meanwhile, nickel oxide at the cathode accepts electrons and releases nickel ions (Ni^{2+}).

Throughout both charging and discharging phases, charged ions, encompassing nickel ions and hydrogen ions, journey back and forth between the anode and cathode via the electrolyte. This reciprocal ion movement is the basis for storing and discharging electrical energy.

The beauty of NiMH batteries lies in their ability to recharge and discharge multiple times owing to the reversibility of chemical reactions occurring at the anode and cathode. NiMH batteries typically provide 1.2 volts per cell, which is slightly lower than the 1.5 volts of alkaline batteries, yet they compensate for this with higher capacity and the reusability factor. It's worth noting that NiMH batteries experience somewhat higher self-discharge rates compared to some other rechargeable batteries, which implies they may gradually lose stored energy over time, even when not in active use. Regular full discharge and recharge cycles help maintain their performance and longevity. Advances in NiMH battery technology are progressively enhancing their capacity and reducing self-discharge rates, contributing to their continued popularity.”

Prompt 13 & 14:

“how do lead-acid batteries work” & “rephrase it in a few paragraphs”

Answer 14:

“Lead-acid batteries, known for their durability and long history of use, are prominent as rechargeable energy storage devices in various applications, including vehicles and uninterruptible power supplies. The core of a lead-acid battery's operation hinges on electrochemical reactions taking place between lead dioxide (PbO_2) and sponge lead (Pb) immersed in a sulfuric acid (H_2SO_4) electrolyte. Here's a simplified elucidation of how lead-acid batteries function:

A standard lead-acid battery is composed of crucial components, including the positive plate (made of lead dioxide), the negative plate (consisting of sponge lead), a separator to prevent short-circuits between these plates, and the electrolyte, a dilute sulfuric acid solution that enables ion flow between the plates.

During discharge, when the battery is employed to power a device, the lead dioxide at the positive plate (anode) reacts with the sulfuric acid (H_2SO_4) in the electrolyte, leading to the formation of lead sulfate ($PbSO_4$) at the positive plate. Simultaneously, electrons are released at the anode, setting in motion an electric current that provides power to the connected device.

Conversely, when the battery is being charged, a reverse chemical process unfolds. Lead sulfate at the positive plate undergoes conversion back into lead dioxide, while sulfuric acid is regenerated in the electrolyte. During this operation, electrons are consumed, effectively reversing the direction of the electric current. Electrons flow from the negative plate (cathode) to the positive plate via an external circuit, constituting the electrical energy.

In both the charging and discharging phases, sulfate ions (SO_4^{2-}) traverse between the plates through the electrolyte, ensuring a balanced electrochemical environment. Lead-acid batteries typically deliver around 2 volts per cell, and they are employed in numerous applications by connecting multiple cells in series to achieve the desired voltage. Although these batteries possess commendable qualities like cost-effectiveness and high current output, they necessitate regular maintenance, particularly for flooded (wet-cell) types to monitor water levels. Additionally, due

to the emission of hydrogen gas during charging, they should be used in well-ventilated spaces to mitigate potential flammability concerns.”

[GPT – Power Circuits]

Prompt 1:

“i am writing a IEEE project report and i am currently on the topic of the power supply. can you explain how buck converters work”

Answer 1:

“Certainly! A buck converter, also known as a step-down converter, is a type of DC-DC power converter that takes a higher input voltage and reduces it to a lower output voltage with increased current. Buck converters are widely used in various electronic devices and power supplies to efficiently provide the required voltage levels.

Here's how a buck converter works:

1. **Input Voltage**: The buck converter starts with an input voltage (V_{in}) that is higher than the desired output voltage (V_{out}). The input voltage can be from a power source such as a battery or an external power supply.
2. **Switching Element**: The key component of a buck converter is a switching element, typically a semiconductor switch (often a MOSFET). The switch is used to control the flow of current through the circuit. When the switch is closed, current flows through the circuit; when it's open, no current flows.
3. **Inductor (L)**: Connected in series with the load, the inductor stores energy when the switch is closed and releases it when the switch is open. This helps smooth out the voltage and current.
4. **Diode (D)**: A diode is connected in parallel with the inductor. It allows current to flow in one direction and blocks it in the reverse direction. The diode is necessary to provide a path for the inductor's energy when the switch is open.
5. **Output Capacitor (C)**: The output capacitor is connected in parallel with the load. It helps stabilize and filter the output voltage, reducing ripple and noise.

Here's how the operation of a buck converter proceeds:

1. When the switch is closed (turned on), current flows from the input voltage source through the inductor and into the load. At this time, the inductor stores energy in its magnetic field, and the diode is reverse-biased and blocks current flow through it.
2. When the switch is opened (turned off), the inductor releases the stored energy. The inductor's energy is transferred to the output capacitor and the load. During this phase, the diode becomes forward-biased and provides a path for the inductor's energy to flow to the load.
3. The switching between these two states happens at a high frequency, controlled by a pulse-width modulation (PWM) signal. By adjusting the duty cycle (the ratio of time the switch is on to the total switching period), the output voltage can be controlled. Increasing the duty cycle leads to a higher output voltage, while decreasing it results in a lower output voltage.

The key advantages of a buck converter are its high efficiency, small size, and ability to provide a stable and regulated output voltage even when the input voltage varies. However, it's important to

consider factors like component selection, switching frequency, and output current requirements when designing a buck converter for a specific application.”

Prompt 2:

“can you rephrase it in a few paragraphs”

Answer 2:

“Certainly! A buck converter, also known as a step-down converter, is a type of DC-DC power converter widely used to efficiently reduce a higher input voltage to a lower output voltage. It operates as follows:

The buck converter consists of several key components: an input voltage (V_{in}), a semiconductor switch (usually a MOSFET), an inductor (L), a diode (D), and an output capacitor (C). When the switch is closed, current flows from the input source through the inductor into the load, storing energy in the inductor. During this phase, the diode blocks the current. When the switch is opened, the inductor releases its stored energy, transferring it to the output capacitor and load, with the diode allowing this energy flow.

This switching process occurs rapidly at a controlled frequency, thanks to pulse-width modulation (PWM). By adjusting the duty cycle (the time the switch is on relative to the total switching period), the output voltage can be precisely regulated. Buck converters are prized for their high efficiency, compact size, and the ability to provide a stable output voltage despite input voltage variations. When designing a buck converter, it's crucial to consider factors such as component selection, switching frequency, and output current requirements to match specific application needs.”

Prompt 3 & 4:

“Can you explain boost converters too?” & “rephrase it in a few paragraphs”

Answer 4:

“A boost converter, also referred to as a step-up converter, is a type of DC-DC power conversion device with the primary function of raising a lower input voltage to a higher desired output voltage. Its operation can be broken down as follows:

The essential components of a boost converter include an input voltage (V_{in}), a semiconductor switch (usually a MOSFET) responsible for controlling current flow, an inductor (L), a diode (D), and an output capacitor (C). When the switch is closed, current flows from the input source through the inductor, and this phase results in the storage of energy in the inductor. Simultaneously, the diode blocks current flow in the reverse direction.

When the switch is opened, the stored energy in the inductor is released. What distinguishes the boost converter is the way in which this energy is transferred to the output. Rather than simply passing it along, the boost converter adds this energy to the input voltage, consequently increasing the output voltage.

The operation of a boost converter is managed through pulse-width modulation (PWM), where the duty cycle of the switch is adjusted to control the output voltage level. A longer switch-on time leads to a higher output voltage, while a shorter switch-on time results in a lower output voltage. Boost converters are often used in scenarios where the input voltage is lower than the required output voltage or subject to variation. This is particularly valuable in applications like battery-

powered devices, where the voltage must be elevated to efficiently power other electronic components. Boost converters excel in their ability to efficiently raise the output voltage while delivering a consistent and stable power supply for a range of electronic devices.”

Prompt 5:

“write a few paragraphs about how low dropout regulators work”

Answer 5:

“Low Dropout Regulators (LDOs) are essential electronic components used to ensure a stable and precise output voltage, even when the input voltage is only slightly higher than the desired output voltage. They play a crucial role in various electronic devices, providing a reliable power supply for sensitive components like microcontrollers, sensors, and RF circuits. Here's a closer look at how LDOs work.

At the core of an LDO is the pass transistor, typically a MOSFET, which serves as a valve controlling the flow of current from the input voltage to the output. The key challenge for LDOs is to maintain a stable output voltage when the input voltage drops, and this is where their low dropout feature comes into play.

LDOs employ a feedback mechanism to continuously monitor and adjust the output voltage. They have an internal voltage reference, often implemented as a bandgap voltage reference, that establishes the desired output voltage level. An error amplifier continuously compares the actual output voltage with the reference voltage. When any deviation is detected, the error amplifier generates an error signal.

This error signal guides the pass transistor's operation. If the output voltage falls below the desired level, the pass transistor opens up, allowing more current to flow and thus increasing the output voltage. Conversely, when the output voltage exceeds the desired level, the pass transistor reduces current flow to lower the output voltage. This continuous feedback loop ensures that the output voltage remains regulated, even when the input voltage is close to the output voltage.

To further stabilize the output voltage and reduce voltage fluctuations, LDOs are often equipped with an output capacitor. This capacitor helps mitigate transient voltage changes and provides additional filtering to ensure a clean and steady power supply.

One of the notable advantages of LDOs is their simplicity, low noise characteristics, and fast response to load changes. However, they are less efficient than switching regulators, as any excess energy is dissipated as heat in the pass transistor. Nonetheless, LDOs are widely used in applications where precision and low dropout performance are critical, making them a valuable tool in the world of electronics.”

Prompt 6:

“write a few paragraphs about how solar cells work”

Answer 6:

“Solar cells, often referred to as photovoltaic (PV) cells, are the core components of solar panels and are responsible for converting sunlight into electricity. Their operation is grounded in a fascinating phenomenon known as the photovoltaic effect. Here's how solar cells work:

Solar cells are typically made from semiconductor materials, with crystalline silicon being the most common choice. When sunlight, which consists of tiny packets of energy called photons, strikes the surface of a solar cell, some of these photons are absorbed by the semiconductor

material. This energy absorption excites electrons in the semiconductor, causing them to jump from a lower energy state to a higher one.

The semiconductor material in solar cells is specially designed with a p-n junction. The p-side is doped with materials that create an excess of positive "holes," while the n-side is doped to have an excess of electrons. This difference in doping creates an electric field at the junction. When the excited electrons and "holes" are generated, the electric field in the cell separates them. Electrons are pushed toward the n-side, while holes are pushed toward the p-side. This separation of charges results in the generation of an electric current.

Metal contacts on the surface of the solar cell collect the liberated electrons and facilitate their transfer to an external circuit. The flow of electrons in the external circuit creates electric current, which can be harnessed to power various electrical devices, charge batteries, or be fed into the grid for broader use.

Solar cell efficiency is a crucial factor, and it represents the proportion of incoming sunlight that can be converted into electricity. The efficiency of commercially available solar cells typically ranges from 15% to 22%, although advanced designs have achieved even higher efficiencies. Solar cells have become a key component of renewable energy systems, contributing to the global shift toward clean and sustainable energy sources. They are used in diverse applications, from residential and commercial solar installations to powering spacecraft in space exploration missions.”